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AD847521

SUPERSONIC AIRCRAFT FUEL TANK FIRE HAZARD INVESTIGATION

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DYNAMIC SCIENCE, A DIVISION
OF MARSHALL INDUSTRIES

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TECHNICAL REPORT AFAPL-TR-68-106

DECEMBER 1968

AIR FORCE AERO PROPULSION LABORATORY

AIR FORCE SYSTEMS COMMAND

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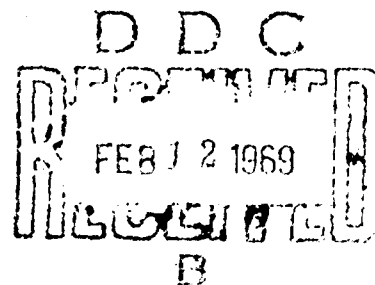
FOREWORD

This final report documents work performed by the Dynamic Science Division of Marshall Industries, 1900 Walker Avenue, Monrovia, California. This effort was sponsored by the Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio, under contract NO F33615-67-C-1553 in support of Air Force Project 3048, Task 304807, "Aerospace Vehicle Hazard Protection." The period covered by this work was from 31 March 1967 to 30 June 1968. All technical phases of this contract were jointly monitored by NASA, FAA and the Air Force with Mr. B. P. Botteri of the AFAPL(APFL) responsible for overall program administration. Mr. Norman L. Helgeson of Dynamic Science was technically responsible for the work. Other Dynamic Science personnel contributing to the contract were: B. R. Lawver, Laboratory Supervisor, W. R. Yates, Research Staff, B. P. Breen, Director of Combustion Research, and members of the staff of Dynamic Science's AvSER Testing Facility. This report was submitted by Mr. Norman Helgeson 30 November 1968.

Publication of this report does not constitute Air Force Approval of the report findings or conclusions. It is published only for the exchange and stimulation of ideas.

Charles R. Henning

γ~ Arthur V. Churchill, Chief
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SUPERSONIC AIRCRAFT FUEL TANK FIRE HAZARD INVESTIGATION

N.L. HELGESON, M. GERSTEIN AND B. P. BREEN

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OF MARSHALL INDUSTRIES

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ABSTRACT

The severe operating environment associated with advanced supersonic and hypersonic flight causes conditions which may significantly reduce the fire safety of these flight systems. The new problem areas arise, in part, from the high temperature produced by supersonic flight through the atmosphere and also from new design concepts. The nature and causes of new fire hazard problems were described in detail in Ref. 1 and those areas requiring further study were pointed out in that survey report.

The purpose of this work was to supplement survey reports which could only postulate problem areas but could not define absolute limits. This was accomplished by carrying out experiments which determined the actual conditions for which a potential fire hazard might exist.

The thermal ignition boundaries for two potential SST fuels as a function of the fuel/air ratio and pressure were defined using a small (1.5 ft^3) test tank in which the fuel and air were uniformly mixed. The effects of wall heating rates, cool walls, and several typical fuel additives on ignition temperatures were also determined. Finally, a large test tank (≈ 15 ft^3) was designed and constructed in order that anticipated nonuniformities in internal fuel tank conditions could be simulated by programming dynamic SST flight profiles. It is also anticipated that the large test tank will aid in extrapolating experimental results to full-scale systems. The large tank was tested with several flight profiles and was found to be capable of reliably simulating flight pressure and temperature profiles. Data runs with the larger tank using two different fuels showed that luminous reactions appeared during the descent portion of simulated SST flight profiles.

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SECTION I

INTRODUCTION

The severe operating environment associated with advanced supersonic and hypersonic flight systems causes conditions which may significantly reduce the fire safety of these systems. The problems associated with these high performance flights include most of those present in conventional aircraft operation as well as some additional problems not present in subsonic aircraft. The new problem areas arise, in part, from the high temperatures produced by supersonic flight through the atmosphere and also from new design concepts which affect fire hazards. The possibility that the major fuel storage areas may be in the fuselage for a supersonic transport, for example, poses problems which differ from those associated with wing tanks in conventional subsonic aircraft. In order to assure adequate margins for fire safety in these systems, it is necessary to first define the nature of the fire hazard and the operating conditions under which the hazard exists and then to develop design criteria or fire protection techniques to provide the necessary fire safety capability.

An investigation to define the various hazardous situations which could arise because of the existence of a combustible mixture and an ignition source during SST flight was initiated by the survey report "Fire Protection Research Program for Supersonic Transport" (Ref. 1). A comprehensive and critical analysis in terms of the various phenomena that might be expected to occur during SST flight was provided and several areas where additional experimental data were considered necessary for the evaluation of possible hazardous situations were indicated.

A particular fire hazard problem which could arise is associated with the fuel tanks and results from the aerodynamic heating of SST fuel tank walls at Mach 2.7 - 3.0 flight speeds. Temperatures up to $500^\circ F$ and flight altitudes to 70,000 feet are anticipated and the nature and extent to which these conditions could cause oxidation and combustion reactions to occur within the fuel tanks were not well defined. Slow oxidation reactions, cool flames, and normal ignitions resulting from either single or two-stage ignition processes could all occur. Of course, it is the normal ignition that is of major concern to aircraft designers because of its greater potential to cause structural damage to the aircraft. But the occurrence of the oxidation and cool flame reactions are of importance as they could induce a normal ignition to occur within the fuel tank via a two-stage ignition process. Because of the questionable margin of safety that exists in these situations an experimental program (Ref. 2) was undertaken to provide a more definitive basis for evaluating the fire hazard and also to consider means of controlling it. Experimental data were obtained to determine the temperature zones of luminous reaction and ignition for mixtures of JP-4, JP-6, a low volatility fuel FS65-3 and n-decane in air. As practical fuels are mixtures of various hydrocarbons, the pure hydrocarbon, n-decane, was included to serve as a reference point. Variables in the tests were the fuel/air ratio and pressure. The ignition characteristics of these fuels in the presence of potential flame inhibiting agents and under conditions of simulated aircraft descent showed that luminous reaction limits extended to fuel/air ratios of several times those predicted for normal flames (Ref. 2).

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In the current program additional studies were completed on the ignition characteristics of two additional candidate SST fuels, Turbine Fuel Type "A" and JP-5. A small (≈ 1.5 ft^3) test tank allowed ignition phenomena occurring under conditions simulating SST flight to be studied. It was desired to make the test equipment sufficiently small so that it would be adaptable to laboratory operations, but at the same time it was necessary that the test chamber be large enough to eliminate wall-quenching effects. Other features were incorporated so that the temperature of the tank wall and the pressure in the tank could be controlled at the desired levels and so that appropriate measurements could be made. Temperature zones for luminous reactions and autogenous ignition were mapped for a range of fuel/air composition ratios at several pressures. Additional tests determined the effect that wall heating rate, a cool wall, and typical fuel additives have on the zones of ignition of fuel/air mixtures.

Concurrent with the conclusion of the small tank test program a large tank was constructed in order to extrapolate the small tank tests to more realistic conditions of size and pressure/temperature dynamics. This tank possesses the capability of dynamically simulating internal fuel tank conditions for long term SST flight profiles. Because of its size and complexity a considerable portion of the program effort was involved in assembling the test tank with its various controls and instrumentation. It is located at the Dynamic Science AvSER Testing Facility in Phoenix, Arizona. At the end of the current program the tank had been used successfully to obtain data during ten (10) experimental SST flight profiles.

Dynamic flight profiles with the large tank demonstrated that luminous reaction zones exist, as they did in the small scale tests. Thus results of tests conducted with this tank serve as a check on the results obtained from the small tank tests and also can be used to define influential scaling parameters.

SECTION II

SMALL TANK STUDIES

Flame boundary studies previously reported (Ref. 2) have been extended to Turbine Fuel Type A and JP-5 in the present program. These boundaries consist of determination of the luminous reaction zones and autogenous ignition temperatures for fuel/air mixtures at several pressures and compositions. So that the results may be used for evaluating the potentially hazardous conditions which may exist in the SST fuel tanks during flight the experimental conditions and procedures that were used were chosen to simulate, to a large extent, the actual SST fuel tank conditions.

A detailed description of the small SST fuel tank simulator is provided below and the sections following it describe tests that were conducted, the test procedures used and the results obtained.

1.   APPARATUS

The small SST fuel tank simulator (1.5 ft^3 volume) is shown schematically in Figure 1. It is constructed of $0.050 - 0.010$ inch stainless steel and is twelve inches in diameter and twenty-five inches long. The upper hemispherical end is removable to permit free access to the interior of the vessel. The vessel is designed to withstand a pressure of 300 psia. A continuous coil is wound around the outside of the tank to provide for rapid cooling by the passage of a suitable fluid through these coils.

The tank is heated by four heating elements with a total power rating of 2.8 kilowatts. The power input to the individual heaters can be varied so that a uniform wall temperature may be maintained. The temperatue of the wall is monitored by four thermocouples attached to the exterior of the tank. These thermocouples are shown at TC^1_t through TC^4_t. The vapor temperature is measured at four elevations within the tank by thermocouples which are shown as TC^1_v through TC^4_v.

The tank is equipped with a burst disc assembly fitted with a 2" burst disk with a rating of 105 psia at $72°F$. It is also equipped with a Pyrex window which was used for either photometric or photographic detection of light emitted during the studies. The reaction pressure is monitored by a 0-30 psia pressure transducer calibrated against a mercury manometer. Fuel, air, and additives are added to this chamber through a port near the top. The chamber is also equipped with two gas sampling probes, one seven inches from the top and the other seven inches from the bottom.

2.   FLAME BOUNDARIES

Ignition boundary data for the candidate SST fuels: (TFA) Turbine Fuel Type "A" (ASTM-D-1655-66T Jet A) and JP-5 are presented in this report. Data were obtained as a function of pressure and initial vapor phase composition of the fuel/air mixture. A specification sheet for TFA is given in the Appendix, Table I. JP-5 was provided by the Air Force.

a. Test Procedure and Definitions

In each test, the test tank (Fig. 1) was evacuated and heated to 300°F. A prescribed amount of liquid fuel was then injected into the tank where it evaporated. Air was added to yield the desired fuel/air ratio and total pressure. The ratio of the fuel pressure to that of the air pressure within the tank was used to determine the initial composition for the test which was reported on a volume-per cent basis.

After the desired sample was obtained in the test tank the test was initiated by uniformly increasing the temperature of the tank and its contents at a rate of approximately 20° F/minute up to a maximum temperature of 650°F. Throughout the course of the test the pressure was held constant by appropriate use of a pressure regulating system. The outputs from several of the thermo-couples, the photomultiplier tube, and the pressure transducer shown in Figure 1 were monitored on strip chart recorders. Tests were conducted for initial fuel/air volume compositions of 1, 3, 5, 10, 20, 30, and 40 per cent at pressure levels simulating flight altitudes of sea level, 20,000, 25,000, 40,000, 60,000, and 80,000 feet.

The data obtained were of the form shown in Figure 2. It was recorded on separate instruments that were set to the same time scale and the traces have been superimposed here to show the correspondence of the measured parameters. The three traces represent the output of a photomultiplier tube, a pressure transducer and a vapor phase thermocouple, and the results shown distinguish the two types of flame phenomena that were observed to occur. The first, which is called an "ignition" was identified where light, temperature, and pressure changes occurred coincident to one another. The light intensity was, in general, very high at these times and in most cases was off-scale. Both cool-flame and normal-flame ignitions are included in the term "ignition" (see Discussion Section). The second type of flame phenomena observed in these tests was one for which light emission was detected but for which no temperature or pressure perturbations occurred. This phenomenon is referred to as a "luminous reaction." In the test results of Figure 2 "luminous reaction" is seen to occur both before and after the time of ignition and its occurrence extends over a period of time.

Figure 2 shows that the pressure was maintained at a constant value during the test except for an abrupt increase following the "ignition." The rate of return of the pressure of the system to the value existing prior to ignition was controlled, of course, by the characteristics of the constant pressure regulating system. The change in pressure that was measured may be used as an indication of the relative strength of the ignitions which occurred during the tests.

The indicated temperature change at ignition does not accurately represent the maximum temperature change obtained in the vapor phase. The thermo-couples were contained in stainless steel sheaths to prolong their usefulness, and as a result, the sheath introduced a time lag which prevented monitoring changes in temperature environment that were faster than one cycle per second. The temperature response was sufficiently rapid, however, to provide confirmation of the occurrence of ignition. The leveling off of the temperatures after ignition is due both to the expansion of the combustion gases as the pressure returns to its original value and to the transfer of thermal energy to the walls of the test tank.

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b. __Test Results__

The large amount of test data that has been accumulated is presented in tabular and graphical form. Generally, the experiments involved heating a specific fuel/air mixture at a specified simulated altitude and observing the temperature at which the luminosity and sequential flame occurred such as in Figure 2. The tabulated data for TFA/air and JP-5/air present a complete summary of all data recorded; while the graphical presentation is an attempt to present this data in more usable or more interpretable form. The large number of graphs demonstrate both the range of luminous reactions and the temperatures of ignition for

(1)   Altitudes from zero to 80,000 ft for each fuel volume **percent.**

(2)   All fuel percentages for each altitude.

Turbine Fuel Type A. The results of the flame boundary tests for TFA are given in Table VI in the Appendix. The test results are grouped according to the initial composition for the test and are listed in an order of decreasing pressure within each group. In tests 1-28 the amplification of the photomultiplier tube recording circuit did not indicate the presence of low level light emissions. The photomultiplier signal was amplified in later tests and luminous reactions were observed. Those tests conducted without amplification of the photomultiplier signal are indicated by the letters, "W.A." in the column under luminous flame temperature.

The individual tests plotted in Figures 3 to 9 show observed ignition temperatures versus simulated altitude (pressure) for a particular initial composition. Each test is described by a vertical line and the square associated with it. A solid line represents the occurrence of a luminous reaction. The square represents the occurrence of an "ignition" which is accompanied by rapid changes in the temperature and pressure of the mixture, and dashed lines represent continuing tests where no observable reactions occurred. Luminous flames sometimes persisted to temperatures above the scale of the Figures and this is indicated by an arrow at the limit of the plot.

A fair amount of scatter does exist in the ignition limit data. Therefore, as is typical of the statistical nature of ignition limits, the specification of a lower ignition limit is not justified. However, the ignition temperature appears to decrease with increasing pressure as in Figure 10. In an attempt to uncover an experimental condition which could lead to consistent scatter in the results the variations in heating rate were examined. The nominal heating rate for the tests was $20°F/min$, but experimentally this heating rate ranged from $17-28°F/min$. However, no consistent deviation of the results could be attributed to variation in heating rate.

The accuracy of the temperature measurement might also be considered as a possible source of ignition scatter. Extensive data on the test tank temperature profile are given in the section on cool wall tests. These data indicate that temperature variations that may exist within the tank could not account for the amount of scatter in the ignition data that is reported.

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The data for the occurrence of an ignition in Figures 3-9 have been replotted in Figure 10 and a line indicating a lower ignition limit has been drawn. As mixtures of all compositions are included on the figure the lower ignition limit applies to that mixture having the lowest autogenous ignition temperature at the specified pressure. Several of the experimental points are at considerably lower temperatures than the others and this fact again points out the statistical nature of raw ignition data. However, as the tests were run from the point of view of determining margins of safety for aircraft operation the lower test points must be considered in specifying a lower ignition limit.

The data can be cross-plotted as shown in Figure 11 using pressure (altitude) as a parameter. A lower ignition limit is indicated for the data taken at each altitude. The curves shown were drawn to include the lowest measured ignition temperatures and within the scatter of the data then exhibited in general, a monotonic increase in ignition temperature with altitude as might be expected.

JP-5. The results of the flame boundary tests for JP-5 are given in Table VII of the Appendix, and, in general, the same comments apply here as were made regarding the results for TFA. The data are presented graphically in the same manner as was done with TFA in Figures 11 to 16. A composite of the ignition data is plotted in Figure 17 and a lower ignition limit is indicated. Figure 18 shows a cross plot of the data with altitude as a parameter. (See Figure 35 for an example of how the lower ignition limit was specified from the results of tests conducted at a simulated altitude of 25,000 feet).

c. Discussion

The test results are largely self-explanatory presentations of the limits within which ignition has or has not been observed. This discussion is an attempt to clarify what was observed and to compare the limits with other data.

Vapor Composition. As chemical analyses of the vapor phase were not obtained during the tests other than for the initial ratio of pressure, the compositions were reported in terms of the initial compositions. For the cases where no chemical reaction occurred in the test tank during the heat-up period of a test the initial composition would be an accurate indication of the conditions which existed at the time of ignition. However, some chemical reaction probably did occur during the heat-up period, particularly in those tests where a "luminous reaction" was observed prior to ignition. The initial compositions that were used, however, seemed to provide a complete range of compositions that would be of interest in these tests. That is, the F/A ratio varied from 1-40 volume per cent and the severity of the ignitions that were observed had decreased to very low levels for the high F/A ratios (see Tables VI and VII in Appendix).

Flame Terminology. Some further consideration of the flame terminology discussed above will be given at this point. The "cool flame," in general, is a low-temperature (400-500°F) reaction that results in temperature and pressure changes of relatively low order (e.g. temperatures changes up to 180°F). It is an incomplete reaction (i.e., it does not proceed to thermodynamic equilibrium) and because of this it r y appear and disappear several times in a given

test. It occurs over wide ranges in composition. The "normal flame" is a very energetic reaction producing large changes in temperature/pressure and follows either a single or two-stage ignition process. (Note: this is in contrast to some references where a normal flame is distinguished from a 2nd stage flame, Ref. 3).

If a normal flame occurs by a single stage ignition process it occurs only over a relatively small range in composition. Table II shows the composition limits for a single-stage ignition and the variation of these limits with temperature for a representative hydrocarbon, n-pentane, (Ref. 1).

The two-stage ignition process may occur over a relatively wide range of composition and gets its name from the fact that the normal flame is preceded by a cool flame which yields certain intermediate reaction products required for the second-stage ignition. The severity of the reactions resulting from this second-stage ignition may range from pressure/temperature changes only somewhat greater than is obtained from cool flame ignitions to the changes that are nearly as great as those associated with the single-stage ignitions. Additional discussion regarding the two-stage ignition process may be found in References 3, 4, 5, and 6. The main point is that the two-stage (1. cool flame to 2. normal flame) ignition process occurs over wide composition ranges while flame severity decreases away from the narrow single-stage limits.

The initial compositions that were used in the tests ranged from 1-40 per cent by volume. Since the lean and rich limits for normal combustion of turbine fuels are approximately 1 and 5% by volume, in tests where the composition was initially much greater than 5%, the ignition must have occurred via a second-stage ignition process which followed either a cool flame, or possibly, a preflame auto-oxidation reaction. Thus for the very rich mixture (30 and 40 volume per cent fuel) it is possible that second-stage ignition did not occur and that the weak ignitions observed were cool flame ignitions. Lending credence to this supposition is the fact that the ignitions observed for the rich mixtures were all very weak. Successive pressure pulses which would be anticipated in a two-stage ignition were observed in some tests, but not others. On the other hand the pressure pulses could have been sufficiently close together on some of the tests so that the instrumentation did not respond rapidly enough to distinguish them. As sufficient information does not exist to determine whether the ignitions observed were cool flame or 2nd stage ignitions both types have been included in the term "ignition."

Comparison with Literature. A previous study by Lockheed-California (Ref. 7) presented data on the ignition properties of Turbine Fuel A for conditions simulating certain aircraft fuel environments. Data obtained in Reference 7 were not exactly the same as those obtained in the current tests but results of the most similar tests can be compared.

The tests discussed in Reference 7 were run to evaluate the fire/explosion hazard in the dry bays which were to be placed adjacent to the SST fuel tanks. Liquid fuel was injected into the dry bay after the bay had been heated to the desired temperature and evacuated to the desired altitude. Tests were run both with and without ventilating air being forced through the dry bays and also with a drain either in the open or closed position. The results referenced here will be only the nonventilated tests but with the drain open and closed.

A temperature range of 450-750°F was considered with the dry bay simulator altitude varying from 10-70,000 ft. The fuel/air ratio was varied over the range of .048 to 2.0 (approx. 1-40% by volume) by weight as determined by an initial material balance; i.e., calculating the weight of air that would be present for the given conditions, and then injecting a known amount of liquid fuel to give the desired F/A ratio. After the fuel was injected into the tank, the tank interior was monitored for pressure and temperature changes and was observed visually for luminous reactions. This was continued for up to two minutes or until an ignition of the mixture was detected. No instrumentation was employed for the detection of luminous reactions and the composition existing within the dry bay was not monitored except for the initial determination.

Results for the two conditions of interest are shown in Figure 20 where they are compared with results of the present test program. These lower ignition limits were derived from the lowest ignition temperature obtained over the range of compositions tested. It is seen that the results for both types of tests reported in Reference 7 indicated higher minimum ignition temperatures than was obtained in the current tests for TFA. The maximum pressure changes reported also were much lower than in the present tests. (ΔP max ≈ .1 psi). Although no definitive evidence can be presented to explain the differences obtained, comparison of test procedures particularly in the fuel rich "cool flame" regime show differences in experimental approach and recording instrumentation.

An important difference between the Lockheed data and that reported here (Ref. 7) is that a uniform mixture of the fuel and air within the dry bay was probably never obtained, especially if the time to ignition after injection of the fuel was short (time to ignition was not a reported parameter). A diagram illustrating the nonuniform vapor mixture that could have occurred in these tests is shown in Figure 21. This type of vapor phase mixing may be contrasted to that obtained in the current test where a more uniform mixture existed because of heating method and time periods. In addition to the difference in mixing, the fuel/air mixture undergoes different temperature-time histories in the two types of tests. The Lockheed tests are conducted at constant temperature of the dry bay whereas the current tests underwent a heat-up period.

It is believed that the differences in the test procedures described above could be sufficient to explain the difference in the experimental results. For example, the maximum pressure rise on ignition that was reported in Reference 7 for an altitude of 25,000 ft or above was 0.1 psig for dry bay temperatures up to 750°F. Certainly if an explosive mixture had existed throughout the interior of the dry bay an ignition that propagated through the bay would have generated a pressure pulse of several times this magnitude. In the current tests pressure rises of 1/2 to 3/4 or an atmosphere were measured in tests conducted at a simulated altitude of 25,000 ft. Thus, if the reactants were not uniformly mixed in the dry bay ignitions some data points which would normally be strong could become very weak even to the point of not being detected (instrumentation was sensitive to pressure changes of 0.01 psig). As a fuel surface area in an SST fuel tank will be much greater than that existing in the dry bay tests a much more uniform distribution of fuel/air composition would be anticipated and it becomes somewhat questionable as to how applicable

the Lockheed tests (even though they may well represent the hazard condition of a dry bay) are for evaluating the hazards that may exist within an SST fuel tank. While a somewhat uniform vapor distribution may be an advantage of the present tests a free liquid surface would be required to more nearly simulate the actual SST fuel tank condition. A free liquid surface would, for example, provide a means for replenishing the fuel in the vapor following a preflame reaction. This should be included in future tests.

Another less likely, but possible, cause for weak ignition is that the injected liquid could have been at various stages of oxidation when ignition occurred. This follows from the history of the fuel as it is injected in the high temperature test bay. It is injected as a liquid, the liquid boils, the vapor diffuses and starts reacting as more fuel evaporates. The process continues with the liquid boiling off first having had a greater opportunity to undergo preflame oxidation than that fuel which evaporated later.

The differences pointed out above are not a criticism of the results of either set of data, as the purposes of the two programs were somewhat different: one was to evaluate the explosion hazard in a dry bay, the other to evaluate the hazard existing in a fuel tank. As such, the differences in procedures may well be justified.

3.   WALL HEATING RATES

The effect of tank wall-heating rate variations on flame boundaries was investigated in two series of tests with TFA (see Table VIII in Appendix). One series was conducted at atmospheric pressure and the other at a simulated altitude of 25,000 feet. Heating rates of 2° F/min and 20°F/min were compared in the tests conducted at atmospheric pressure and low fuel concentration (1, 3 volume per cent) with the result that no ignitions were observed with the lower heating rate. At concentrations of 3.7 volume per cent and greater ignitions were obtained for both 2 and 20°F/min heating rates.

In the series of tests conducted at a simulated altitude of 25,000 feet heating rates of 10°F/min and 20°F/min were compared. The results of these tests are plotted in Figure 22 and no consistent variation of results was obtained. No tests were conducted for 1% fuel concentration using the 10°F/min heating rate so that comparisons cannot be made for this lean mixture. From the results of these two series of tests it appears that the wall-heating-rate may have an effect on the degree to which preflame oxidation reaction occurs. This is exemplified by the absence of an ignition in the tests in which low heating rates were used and by the fact that preflame luminous reactions did exist. The tests conducted do not indicate, however, any uniform deviation of the autogenous ignition temperature that could be attributed to the variation of the wall heating rate. This result is in agreement with the Flame Boundary Results (Sec. 2).

4.   SIMULATED DESCENT

At the end of several of the tests described above, air was allowed to enter the tank to simulate aircraft descent rates from 1,000 to 30,000 ft/min. These tests were a cursory attempt to define venting and descent effects.

Descent tests were started whether or not ignition had previously occurred, and after the tank wall had reached 650°F. In most of these tests an ignition had already occurred during the ascent portion of the test using up some of the fuel supply. The experimental results are listed in Table VI and VII for the tests with TFA and JP-5, respectively. They are also plotted in Figures 23 and 24. The coordinates for these figures are initial volume per cent fuel and rate of descent. The initial altitude for the descent would have some effect on the results and this effect can be determined from the tabulated data.

It is seen that the results of the tests may be separated into general areas: that where an ignition occurred, where only luminous reactions were observed, and that where no reaction was observed. The ignition occurred where the initial fuel per cent and the rate of descent were both high. At low initial F/A ratios and low rates of descent no reactions were observed. Luminous reactions, in general, appeared in an intermediate region.

The results are useful to help define the conditions under which a hazard may exist. This applicability is limited by the fact that ignitions occurring during the ascent portion of the profile could have depleted reactants to the point where the composition variable indicated is somewhat inaccurate for the descent portion, especially for low initial F/A ratios. On the other hand, the air used to simulate the descent was at ambient temperature; the effect that a heated air stream could have on the ignition temperature would give somewhat different results.

These tests demonstrate that luminosity and normal ignition may occur in the descent portion of a flight profile even with partially oxidized or previously ignited fuel. More meaningful ignition boundaries could be obtained from experiments conducted when liquid fuel is present and a heated air stream is used to simulate the descent.

5.   COOL WALL TESTS

The effect of cool surfaces on ignition temperatures of hydrocarbon-air mixtures can be predicted from thermal ignition theory (Ref. 8). Consider a combustible gas mixture in a reactor with constant wall temperature. Heat will be produced from chemical reactions within the system and the rate of heat production is described by:

$$\dot{q}_R = vQka^n \exp(-E/RT_g) \tag{1}$$

where
v = reactor volume
Q = heat of reaction
k = reaction rate constant
a = gas pressures or concentrations
E = activation energy of the reaction
R = universal gas constant
T = absolute temperature of the gas

For a given wall temperature, the rate by which heat is lost from the system is directly proportional to the gas temperature as follows:

$$\dot{q}_L \ = \ H(T_g - T_w)S \propto \ \frac{\lambda \ (T_g - T_w)}{\Delta x} \tag{2}$$

where H = heat transfer coefficient

T_g = gas temperature

T_w = wall temperature

S = wall surface area

λ = thermal conductivity of vapor

Δx = characteristic reactor dimension

The relationships between these heat production and heat loss terms and their dependence on gas temperature are shown in Figure 25. Heat generation and heat loss are plotted against the vapor phase temperature. For a given chemical mixture the rate of heat generation may be represented by the exponential curve for $\dot{q}_R$. This is contrasted to the three linear curves representing the heat loss that could occur from the three wall temperatures, T'_w, T_w, and T''_w.

For a system with walls thermostatted to T'_w, $\dot{q}_R$ is larger than $\dot{q}_L$ initially, and the system becomes warmer until it reaches a steady condition at T_g where $\dot{q}_R = \dot{q}_L$. If chemical heating of the gas were to continue past T'_g, $\dot{q}_L$ would become larger than $\dot{q}_R$ and the system would return to T'_g. For some higher wall temperature T'_w, $\dot{q}_R$ is at all times greater than $\dot{q}_L$ and the gas temperature, and hence the reaction rate, continue to increase uncontrolled. It can be seen that there exists some wall temperature T_w which is the highest capable of yielding a system in which $\dot{q}_R = \dot{q}_L$. This is an unstable condition, however, as a slight perturbation toward a higher gas temperature yields the runaway condition $\dot{q}_R > \dot{q}_L$, or thermal ignition. T_w is hence called the minimum thermal ignition temperature of the specific system. This temperature has meaning to other systems only when an analytical model is used to account for geometric, heat transfer and flow scaling.

Consider the effect of maintaining one wall of a reactor at some temperature lower than T_w, the measured ignition temperature in the uniformly heated system. The temperature profile across a reactor all of whose walls are maintained at the ignition temperature T_w is shown in Figure 26a. The gas temperature T_g in a system approaching ignition is always greater than T_w and can be shown to be equal to $\Delta T = RT^2/E$ (Ref. 8). The effect of cooling of the reactor is to increase $\dot{q}_L$ and then decrease the temperature of the vapor phase as shown in Figure 26b. Thus ignition now requires an increase in T_w to counteract the increased heat loss due to the cool wall as shown in Figure 26c.

The proportionality shown in Eqn. 2 also reveals an important result as regards the effect of reactor (or fuel tank) size upon the magnitude of the heat loss and cool wall effect. As reactor size Δx increases, it can be seen that $\dot{q}_L$ decreases, so that at some large Δx the heat loss will become negligible.

Table IX outlines the test plan which was followed and the results that

were obtained in a series of tests that were conducted to assess the significance of a cool wall on ignition temperature. All tests were conducted with 10% Turbine Fuel Type A in air at a simulated altitude of 25,000 feet (282 mm pressure). Temperatures were monitored at four positions on the tank wall and in the top one-fourth of the vapor space (see Figure 1 for thermocouple designations). Tank wall temperatures were programmed upward from a starting temperature of 300°F in all tests not involving cool walls. Cool wall tests 96 and 97 were started at 350°F, while 98 and 99 were begun at 250°F. In order to reveal the possible effect of the ratio of cool wall area to hot wall area, the lower three-fourths of the tank was held at the starting temperature in tests 96 and 98, the lower one-half of the tank wall was kept cool in tests 97 and 99. In all other respects the test procedure used was the same as for those described for the flame boundary studies. The first three entries in Table IX describe, for comparison, the tests that were conducted without a cool wall.

In the flame boundary studies reported above the ignition temperatures were obtained from the vapor phase thermocouple. In the present tests, however, in order to evaluate the results in terms of the ignition theory presented above, it is necessary to consider the value of the wall temperature at ignition. For this purpose the tank wall temperature, TC_t^1 is used. Figure 27 presents a plot of wall temperature at ignition as per cent of the tank wall which was cool. The cool wall temperatures are parameters. The curves drawn in the figure indicate that a cool wall does have some effect on the required wall temperature required for ignition. The increase in wall temperature required for a cool wall at 350° F is small, and could be attributed to experimental inaccuracies. The effect observed where the cool wall temperature is 250°F, however is definite. These results are in qualitative agreement with the ignition theory presented above.

Figure 28 shows the change in measured vapor phase (TC_v^1) temperature for the different cool wall tests. Very little, if any, change was detected where the cool wall represented 50% of the tank wall. However, a large effect is indicated when 75% of the tank wall was cool. In the test where the cool wall was 250°F, the change in vapor temperature was more pronounced. It should be realized that the vapor phase temperature indication is for a specific location within the test tank and that temperatures are probably greater at other locations within the vapor phase. The vapor phase temperatures are given, therefore, to provide an indication of the magnitude of the temperature gradient which existed within the test tank.

Although the data presented is limited, the test results indicate that both the temperature of the cool wall and the area of the cool wall are important in determining the hot wall temperature required for ignition. Other variables which could also have a significant effect on the hot wall temperature required for ignition are the size of the tank and the relative location of the hot and cool surfaces within the tank. (Note: the size is mentioned here only in conjunction with a cool wall. As mentioned previously, it is assumed that the size of the tank is sufficient so that size is not a variable if the walls are heated uniformly.)

6.   FUEL ADDITIVE TESTS

The principal role of an additive in affecting ignition behavior is to act as a source or a sink for free radicals. The additive molecule, if it will have an effect on ignition, may react with active free radicals being generated during the ignition transient and inhibit the rate of further reaction. Higher temperatures would, therefore, be required to obtain a sufficiently high reaction rate to cause ignition. In other cases, the additive molecules may themselves decompose in the high temperature environment. Depending upon the nature of the additive, the decomposition fragments may either inhibit or accelerate the ignition reactions. If the decomposition fragments remove free radicals important to the ignition reactions, then the ignition reactions proceed at a slower rate and higher temperatures would be required for ignition.

A previous study (Ref. 2) showed that certain chemicals, if present in a vapor phase fuel/air mixture, could affect the lower ignition limit of that mixture. The additives tested were selected, partially on the basis of their having sufficient volatility so that the vapor phase would contain an adequate additive concentration. Of the additives tested dimethyamine and tetraethyl lead showed the most promise of being able to increase the autogenous ignition temperatures of the fuel/air mixtures.

Practical fuels for supersonic and hypersonic flight systems will contain several additives to provide a means of controlling various fuel properties such as the viscosity and the dielectric constant. Additives used for this purpose will, generally, be of low volatility so as to minimize their loss from the fuel by evaporation. They could, however, have an effect on the ignition temperature of fuels. To determine the extent of such an effect, several typical fuel additives were evaluated in the current test program using the procedures described above for the boundary tests. Six additives were tested by dissolving them in neat JP-5 in the concentrations indicated in Table III. The solution was injected into the test tank where the additives and the fuel were both allowed to evaporate. All tests were conducted at a simulated altitude of 25,000 feet.

The data obtained are tabulated in the Appendix, Table X, and the results are also plotted in Figure 29 to 34. For comparison, Figure 25 shows the data obtained for neat (additive free) JP-5 at a simulated altitude of 25,000 feet. In contrast to the results presented earlier, mean ignition curves are indicated on the figures as it is believed that these provide a more meaningful comparison of the experimental results than would a comparison of a lower ignition limit curve. The mean ignition curves are plotted together in Figure 36. From these curves it appears that the antioxidant and the lubricity additive may cause an increase in the autogenous inition temperature of the fuel. The other additives apparently have less effect, if any at all.

As might be expected in the tests where the antioxidant was present luminous reactions were never observed prior to ignition. The fact may have great practical significant when fuel residue problems are encounted in application. When the lubricity additive and the antiicing agent were used the frequency of appearance of a luminous reaction prior to ignition was small, whereas in tests where the other additives were used preflame luminous reactions generally appeared.

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These observations tend to support the idea that the luminous reactions may have been suppressed by some of the additives, and that if this is the case, the additives could also be responsible for the slight increase in the autogenous ignition temperatures that were observed when the antioxidant and the lubricity additives were present.

The antioxidant and the antiicing agents are probably the most volatile of all the additives studied, and hence, most likely to be present in the vapor phase. Of these, the antioxidant 2, 6-diteriary-butyl-4-methylphenol is well known as a free-radical former. It is capable of intercepting and terminating autoxidation chains, and therefore, altering free-radical combustion processes. No such action is anticipated from the antiicing agent (methyl cellosolve). The three remaining known additives are extremely nonvolatile and therefore would not be expected to influence the vapor phase processes as much as the two additives described above. The antistatic agent is a chromium salt of a high molecular weight saticylic acid and is probably the least volatile of the additives studied. It does seem to decrease the ignition temperature somewhat, however. The metal deactivator is a high molecular weight amine and the corrosion inhibitor is a derivative of phosphoric acid. The lubricity additive does appear to have some effect on the autogenous ignition temperature and variations of its molecular structure may prove fruitful.

SECTION III

LARGE TANK TESTS

1. EQUIPMENT

A large-scale tank apparatus capable of simulating anticipated internal wing-tank conditions for the SST during flight has been designed and constructed. The tank has a capacity of 110 gallons and is of sufficient size (2 ft. in diameter and 5 ft. in length) to reduce wall quenching effects on flame initiation and propagation. Provision has been made to provide skin heating and cooling rates of up to 5,000 Btu/Hr-ft^2. Original plans had called for fabricating the tank from a titanium alloy, but the excessive cost of this approach required that a different material be used. With the approval of the Air Force, stainless steel 304 was chosen. A shelf has been included in the design of the tank interior so that sheets of titanium or other material can be inserted for test purposes. Access holes have been provided in the tank to permit visual inspection and observation of the tank interior and to provide ports for instrumentation and control purposes. One end of the tank is also removable to permit cleaning and repairs or tank modifications.

The tank structure is built to withstand internal pressure from 0 to 120 psia and provision has been made to supply pressure relief at 70 psia. Altitude simulation equipment for semi-automatic control has been incorporated and suitable instrumentation has been included to provide for monitoring of the temperature of internal tank walls, the vapor space and bulk liquid, the tank pressure, and the composition of the liquid phase. The test tank is shown in some detail in Figures 37-39. Figure 37 shows the general dimensions and layout of the tank. Figure 38 provides a view of the interior of the test tank and Figure 39 shows the exterior of the tank. The wires extending from the top and bottom of the tank in Figure 38 are for thermocouples located at various positions within the tank.

a. Tank Installation

The tank is mounted on a test stand and placed in the center of a 8' x 14' test cell (see Figure 40). The walls of the test cell are 8' high. Three of these consist of an 8" layer of sand contained between 1" sheets of plywood. The fourth wall is a single layer of plywood that is hinged and which opens to form a large entry into the test cell (see Figure 41). The frame of the test cell is of steel girders. A corrugated metal roof has been provided. Adjacent to the test cell and part of the same building is a large room that contains the vacuum pump and some of the control instrumentation (see Figure 42). The remainder of the controls, recorders and instrumentation have been placed inside an air-conditioned laboratory approximately 75 feet from the test site (see Figure 44). The controls and instrumentation have been located such that personnel should never have to enter the test cell during a test. Occasional tasks may require the attention of personnel in the room adjoining the test cell, but otherwise, tests can be completely controlled and monitored from the laboratory location.

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An electrical power source for the immersion and wall heaters capable of supplying 200 amperes at 460 volts has been supplied directly to the test building. Application of the power to the test tank is controlled remotely from the laboratory. Water and compressed air are available in the test cell and a dry-powder fire extinguishing system has been installed. The extinguishing system may be actuated either manually or automatically by means of a fusible link.

    b.   <u>Instrumentation and Control</u>

        (1) Temperature Measurement

        A total of seventeen thermocouples has been provided for measuring temperatures at various internal positions of the tank. The temperatures of several positions in the vapor phase, the liquid phase, and on the unwetted tank wall may be monitored. Exposed thermocouples have been provided for monitoring the vapor phase temperature and remote junctions are used for thermocouples monitoring the liquid phase and wall temperatures. The thermocouple leads are of various lengths and can be adjusted at the port where they enter the tank to reach different parts of the tank interior. Approximately 35 thermocouple clips have been provided on the interior of the tank walls so that the thermocouples can be moved from one place to another and temperatures at the different positions can be compared. Two of the thermocouples are used for input to two feed-back controller systems which independently control the liquid phase temperature and the unwetted wall temperature. Up to twelve (12) of the remaining thermocouples may be monitored on a 12 point Leeds and Northrup strip chart recorder. An oscillograph is also available for recording the thermocouple outputs over short periods of time.

        (2) Temperature Control

        The means by which temperature is controlled is through the use of electrical resistance heaters for heating and cooling coils using water as a cooling medium for cooling the tank walls. The arrangement of the heaters and cooling coils is shown in Figure 45 and 46. The total heating capacity for the external wall heaters is 39 kw and for the immersion heaters is 26 kw.

Two programmer-controller combination sets for independently controlling the liquid-phase temperature and the unwetted tank wall temperature were purchased for use in this program. The controller is an MPRY Thermac Solid State Temperature Controller and the programmer is the Model 5300 Data Trak Programmer. The sets are manufactured by R.I. Controls of Minneapolis, Minn. and are adjusted to operate normally in the range of $0-500^{\circ}$ F using iron-constantan thermocouples. Somewhat higher temperatures (approximately 75°F) may be obtained if a small adjustment is made. The electronic circuit of each controller utilizes an SCR firing circuit to control up to 100 amperes of current supplied at 460 volts.

Each controller may operate in any of three modes: manual, set-point, or programmer. Manual control permits a linear increase in power supplied to the load with an increase in dial setting up to 100%. Set-point provides a means for dialing in a specific temperature to which it is desired the work be controlled and

through the use of the programmer a variable temperature may be specified. Programming is easily accomplished by drawing the desired temperature-time profile on a card coated with a conductive film. When this card is inserted into the programmer a control signal is generated and transmitted to the controller as a control point.

(3) Pressure Measurement and Control

Continuous pressure measurement is obtained by monitoring the output of a Teledyne bonded strain-guage pressure transducer (0-50 psia). The output is recorded on a Texas Instruments strip chart recorder. The ascent portion of a flight profile is obtained by controlling the evacuation rate provided by a Welch Duo-Seal vacuum pump having a capacity of 15.2 ft^3/min. A throttle valve in the 2" evacuation line provides a rough control of the evacuation rate and a fine control is established by supplying an air bleed to the vacuum line via the ascent throttle valve and ascent regulator. The descent portion of the profile is obtained by isolating the vacuum pump and controlling the air bleed rate through the descent throttle and descent regulator. An air inlet heater has been provided in the descent line to heat incoming air to 400-500°F. A nitrogen purge system has been provided to help control undesirable reactions that might occur within the tank and a pressure relief valve set for 70 psia has been included. The pressure control system is schematically outlined in Figure 47.

(4) Flame Detection

Any normal ignition that might occur within the test tank would probably be indicated by abrupt changes of both pressure and temperature. Lower level luminous reactions may occur, however, which would not be detected by either of the above parameters. To detect these low intensity reactions and also to confirm the occurrence of any normal ignition, a photomultiplier tube was installed outside the observation port on one end of the test tank (Figure 48). The observation port at the opposite end of the tank was covered and a small test light was installed under this cover to serve as a check on the operability of the photomultiplier (Figure 49). The continuously monitored output from the photomultiplier tube was recorded on a Varian Associates strip-chart recorder.

(5) Liquid Composition

A Pensky-Martens closed-cup flash point tester was purchased to monitor the changes in the composition of the liquid phase.

2. TEST PROCEDURE

Many prerun checks were conducted with an empty test tank to verify its operational capabilities prior to performing tests with fuel. The tank was heated and circumferential temperature profiles were obtained. From these profiles the location for the reference thermocouple for the unwetted wall temperature controller was chosen. A profile from one of these tests is shown in Figure 50. Several runs were also made to adjust temperature controller gain settings and to

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provide information on the accuracy and reliability of controls. The results of one of these runs is shown in Figure 51.

Data on the liquid phase showed that a large temperature difference (as much as 100°F) existed between the upper and lower layers. The temperature of the liquid was determined at only two levels, however (2" from bottom of tank and 1/2" below liquid-vapor interface), and the degree of stratification or of mixing due to free convection in the large intermediate region is not known at this time. The location for the control thermocouple for the liquid phase was chosen near the liquid-vapor interface (within 1/2"). The ability of the cooling coils that are attached to the walls of the tank to provide adequate cooling was verified. Evacuation tests were performed to determine the degree of tank-atmospheric air integrity. The leak rate was less than 0.5 psi change/day under evacuated conditions. This was judged to be satisfactory. Several experimental runs were undertaken to show that good pressure control could be obtained for the ascent, level flight and descent portions of the flight profile (see Figure 52). A final check run to simultaneously verify operation of all tank control and instrumentation was completed and designated Test 1. All phases of the tank operation were satisfactory.

A total of nine (9) tests for the purpose of obtaining experimental data on the large test tank were completed. Four of the tests included controlled pressure and temperature variations to simulate the ascent, level flight, and descent portions of a flight profile. The remaining tests had only the descent portion of the flight profiles. The assumed flight profiles had nominal ascent and descent rates of 2500 ft/min and level flight altitudes of 65-70,000 ft. Descent rates ranging up to 5000 ft/min were included. The maximum internal wall temperature reached during these profiles varied between 425 and 525°F. All tests were conducted with the tank half full of fuel. Data recorded during these tests included temperatures, pressure, and light intensity as described below.

a) temperature indication at two levels within the liquid phase,

b) temperature indications at several positions along the cirumference of the interior of the unwetted wall,

c) temperature indication at three levels and both ends of the tank in the vapor phase,

d) a continuous monitor of the pressure within the fuel tank,

e) a continuous monitor of the output of a photomultiplier tube which was used to detect any luminous reactions or ignitions,

f) flash point determination of liquid phase at beginning and end of each test.

The fuels tested were of two types: Turbine Fuel A and JP-5. Two different lots of TFA were used. The second lot was obtained to perform check-runs on the first lot and had a flashpoint 16°F below that of the first lot. These fuels are summarized in Table IV.

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3.   TEST RESULTS

A summary of the test results is provided in Table V. The data presented include descent rate, wall temperature, maximum gas phase temperature, liquid temperature, and altitude. If a luminous reaction was detected the altitudes and temperatures are provided for the prevailing conditions when the luminous reaction was first detected during the profile, and for when the luminous reaction disappeared. For the tests where a luminous reaction was not observed similar values are given for altitudes near 25,000 feet and for sea level to provide a basis for comparison. Figure 53 shows the experimental results from test 5C during the period when a luminous reaction was occurring. Figure 54 shows the output obtained from only the photomultiplier tube in test 6A.

The first test was run to check out the heaters and controlling circuits. In Tests 2 and 4 identical flight profiles were used with the first lot of TFA fuel. The results from Test 2 indicate a luminous reaction occurring at several places during the descent profile. Standard post run checks indicated, however, that a light leak existed in the tank which could have influenced the output of the photomultiplier tube. Test 4 was run to check the results of Test 2 but a luminous reaction was not observed. As a result the indication of the luminous reaction in Test 2 is not confirmed.

Test 5 was with JP-5 and included four parts. One was a complete flight profile in which a luminous reaction was not observed. Tests 5B, C, and D had nearly identical temperature ranges but somewhat different descent rates. A luminous reaction occurred in each. In Test 6A, using the second lot of TFA, a luminous reaction was again observed. During the last test, 6B(TFA) control of the rate of descent was a.most completely lost at an altitude of 4000 ft. The pressure, temperature and l.ght emission indicated a normal ignition but it could not be determined which of several equipment or test conditions caused the loss of control.

No change was noted in the flashpoint of the fuels except in one case. At the conclusion of Test 4 (the fourth test with this same fuel), a sample was taken from near the surface of the fuel and near the bottom of the tank. Flash points obtained were $139^{\circ}F$ and $138^{\circ}F$ respectively, which indicates that some concentration gradients did exist within the liquid phase but that they were probably not significant. All other results for this fuel, on Tests 1, 2, and 3 had yielded identical flashpoint values of $138^{\circ}F$. The flashpoint of the JP-5 used in Tests 5A, B, C, D was $152^{\circ}F$ and that of the 2nd lot of TFA used in Tests 6A and 6B was $122^{\circ}F$. The difference in flashpoints noted for the two losts of TFA is not unexpected in commercially available fuels.

4.   DISCUSSION

The results of several experimental tests have been presented, and the occurrence of a luminous reaction has been shown to reproducibly appear under certain conditions and not appear under conditions which are considerably less severe (lower temperatures). The tests were not sufficiently extensive, however, to provide criteria for defining the conditions for the occurrence of the luminous reactions.

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In spite of the high (approximately 500°F) wall temperatures that existed within the fuel tank, the observed temperatures of the gas phase were never greater than 420°F during the descent portion of the profile (see Figure 53). The vapor-phase thermocouples were located on the vertical center line of the tank, however, and if luminous reactions were occurring in areas adjacent to hot spots on the tank wall the gas-phase thermocouples may not have indicated conditions existing where the luminous reaction was taking place. The upper vapor phase thermocouple (located 1-1/2" from top of tank) did appear to indicate a gradually rising temperature during those periods that a luminous reaction was indicated by the output of the photomultiplier tube. This gradual rise cannot be directly attributed to any gas-phase reaction, however, as other temperature instabilities were present. Several temperature measurements of the gas-phase were also recorded on an oscillograph trace. The purpose was to determine if any rapid temperature instabilities or variations were accompanying the occurrence of the luminous reactions. None were observed, but the thermo-couple wire was of sufficient size (1/16" dia.) that small temperature instabilities of a frequency greater than one cps could have been damped out and not recorded.

The gas-phase thermocouples seemed to indicate unstable gas motions within the fuel tank during level-flight when no apparent event could have triggered it. This is believed to be due to the temperature variations which existed within the tank during steady level flight, i.e., hot side walls, a warm top and cold liquid surface. If a relatively cold layer of air was to accumulate along the top center line of the tank it is apparent that at some time during the flight an inversion of the type shown in Figure 55 may occur.

The fact that some stratification existed in the liquid phase during the tests has been discussed previously and results of the flashpoint tests indicated the change in composition of the fuel from one test to the next was extremely small.

The experimental results obtained from the large tank tests may be compared to those obtained with the small test tank. First, it may be noted that the maximum gas phase temperature recorded in the large tank was 420°F. As the ignition observed in the small tank occurred only for vapor phase temperatures exceeding 440°F it is understandable why normal ignition may not have occurred in the large tank tests. It should also be remembered that a cool wall (surface of the liquid) effect existed in the large tank tests and as was shown in Section II this may at times increase the hot wall temperature required to produce an ignition.

During the descent profile luminous reactions were observed to occur in the large tank tests for conditions that were much less severe than those used during the small tank tests. The temperatures were much lower (≈400°F compared to 650°F in the small tank) and the simulated descent rates were, in general, considerably lower. It can be surmised, though, that much higher F/A ratios existed in the large tank at the start of a descent profile than in the small tank. For, although the vapor phase was not sampled in the large tank tests a large liquid surface was present and the liquid surface was near its bubble point (boiling point at a pressure other than atmospheric). It is likely, therefore, that fuel/air mixtures in the large tank at the start of a descent were close to 100% fuel if stratification effects were not important.

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A variable which could have a considerable effect on whether and under what conditions an ignition will occur is the temperatures of the incoming air that was used to simulate the descent. As air at ambient temperature was used for both the small and large tank tests the effect of this variable should be investigated further.

5. RECOMMENDED WORK

The large-scale tests demonstrated that luminous reactions existed in dynamic flight conditions, but the fact that they were not always observed leads to the promise that they may be anticipated and prevented. The question remains as to the conditions under which cool flames and single or two-stage normal ignition will occur in the large test tank. To determine this and to be able to evaluate with confidence what will happen in an actual SST fuel tank it is believed that additional tests should be conducted in the large test tank. These tests should include:

a) Studies to determine the effect of using a heated air stream (up to 450°F) to simulate the descent of an aircraft.

b) A determination of the effect of hot wall area (vary liquid level).

c) Studies to determine the nature and extent of stratification in both the vapor and liquid phases with and without venting.

d) Studies to determine the effect of agitation of the liquid phase.

e) Definition of the effect of a chemical additive on inhibiting luminous reaction, ignition, and fuel residue formation in the large test tank.

SECTION IV

SUMMARY

Experimental testing using the small test tank was completed. Data for determining the thermal ignition boundar'~ of two turbine fuels (Turbine Fuel Type A and JP-5) as a function of composition and simulated altitude were presented and lower ignition limits were specified. A detailed comparison of the results for TFA was made with the results reported by the Lockheed Corporation (Ref. 7) which had also conducted tests to evaluate fire hazards associated with SST fuel areas. The present data provided somewhat lower ignition boundaries than was reported in Reference 7, however, it was shown how different experimental procedures and conditions could account for the difference in results reported.

Tests to determine effect of the wall-heating-rate and a cool wall on the thermal ignition boundary were conducted. For initially low fuel/air ratios no ignitions were observed in tests conducted at very low heating rates (2°F/min). However, other than this effect, no measureable effect of the wall heating rate on the thermal ignition boundary was observed (wall heating rate range 10-27°F/min). Tests involving a cool wall showed that the hot wall temperature required to produce a thermal ignition was affected by both the temperature of the cool wall and the relative area of this cool wall as would ɫ expected. The significance of the cool wall effect to aircraft safety must be evaluated for specific cases.

The effect of six fuel additives on the thermal ignition boundary was determined experimentally. Two additives appeared to cause a slight increase in the autogenous ignition temperature. The others produced smaller effects. The most promising of the additives tested were the antioxidant (2, 6-diteriary-butyl-4-methylphenol) and the lubricity additive.

A large test tank was designed, constructed, and used to conduct several tests. The mechanical operation and control of the tank was verified in several pretest runs and was found to be satisfactory in all respects. Ten tests were conducted with TFA and JP-5 fuels to obtain preliminary information on possible hazardous conditions existing within an SST fuel tank and it was shown that luminous reactions did reproducibly appear during the descent portion of the simulated SST profiles; sufficient tests were not run, however, to determine criteria under which these luminous reactions would appear, nor have the conditions which must exist to obtain cool and normal flame ignition been defined. Some of the variables which could be evaluated in a future test program involving the large test tank and which could have appreciable effect on the conditions existing in an SST fuel tank were indicated.
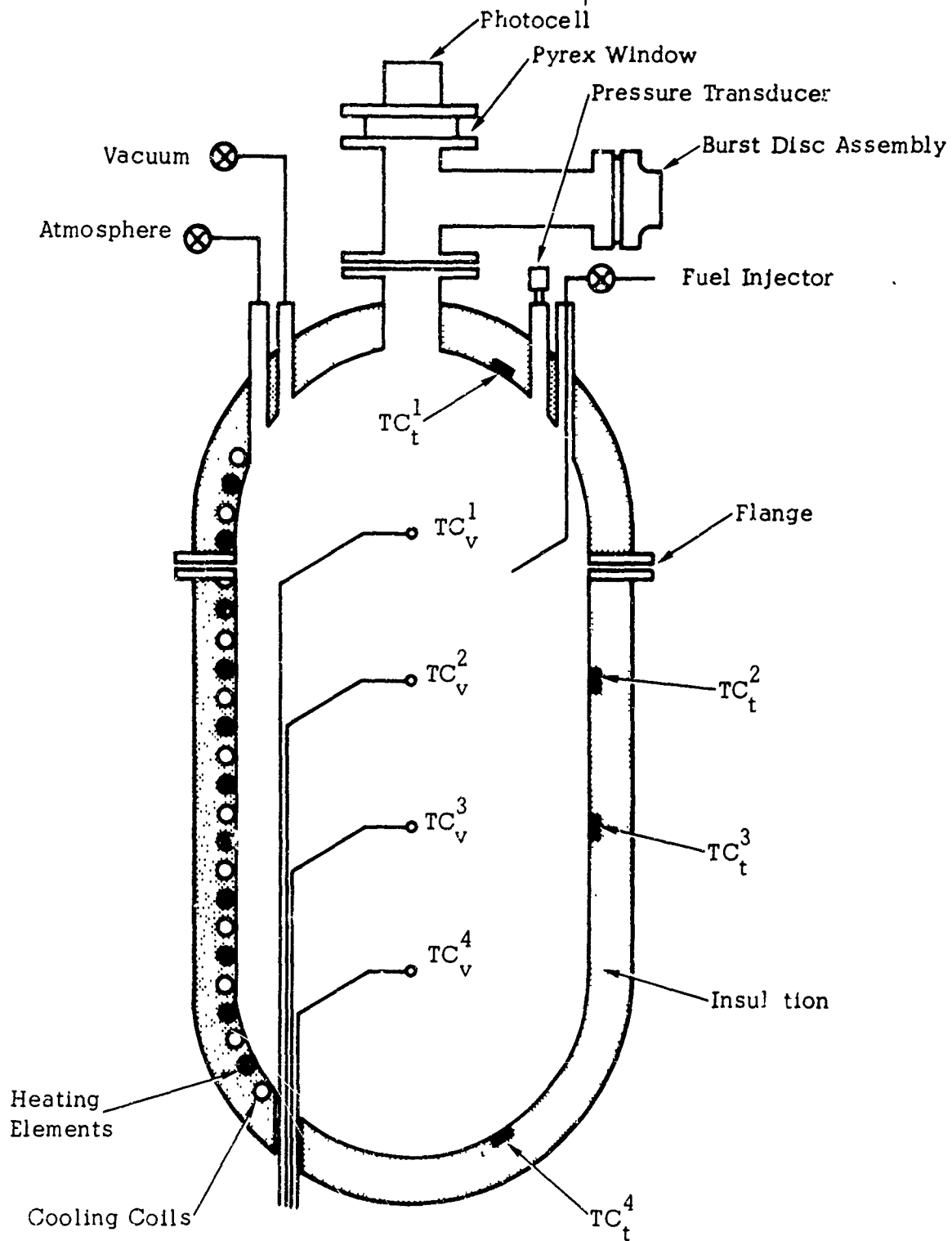
Figure 1. Small SST Fuel Tank Simulator
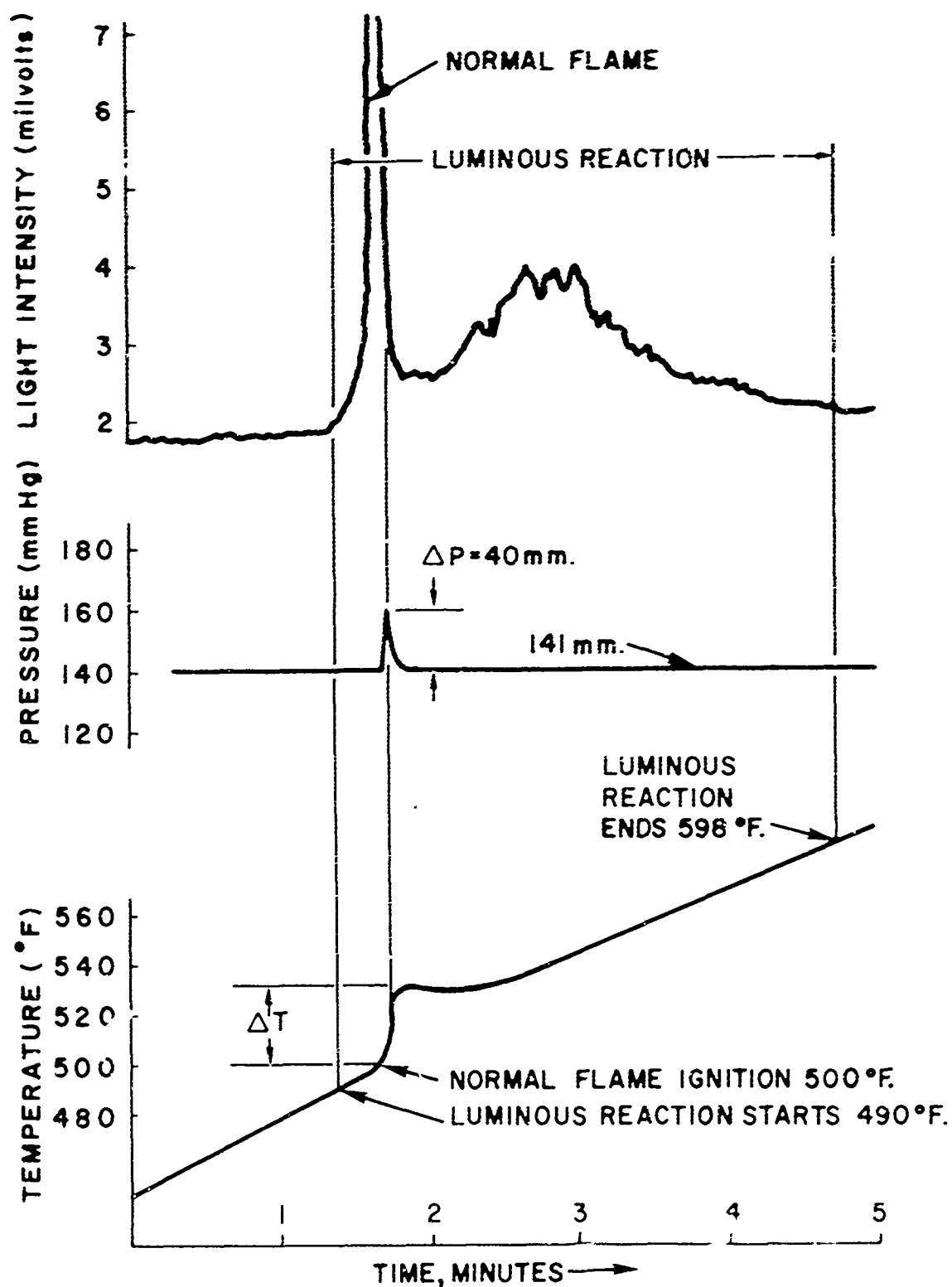
Figure 2.   Data Records from Typical Test in Flame Boundary Studies.
Test No. 51 (25 Vol.% TTA, 40,000 feet).

Figure 3. Ignition Temperature for 1% TFA in Air.

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Figure 4. Ignition Temperatures for 3% TFA in Air.

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Figure 5.   Ignition Temperatures for 5% TFA in Air.

Figure 6.   Ignition Temperatures for 10% TFA in Air.

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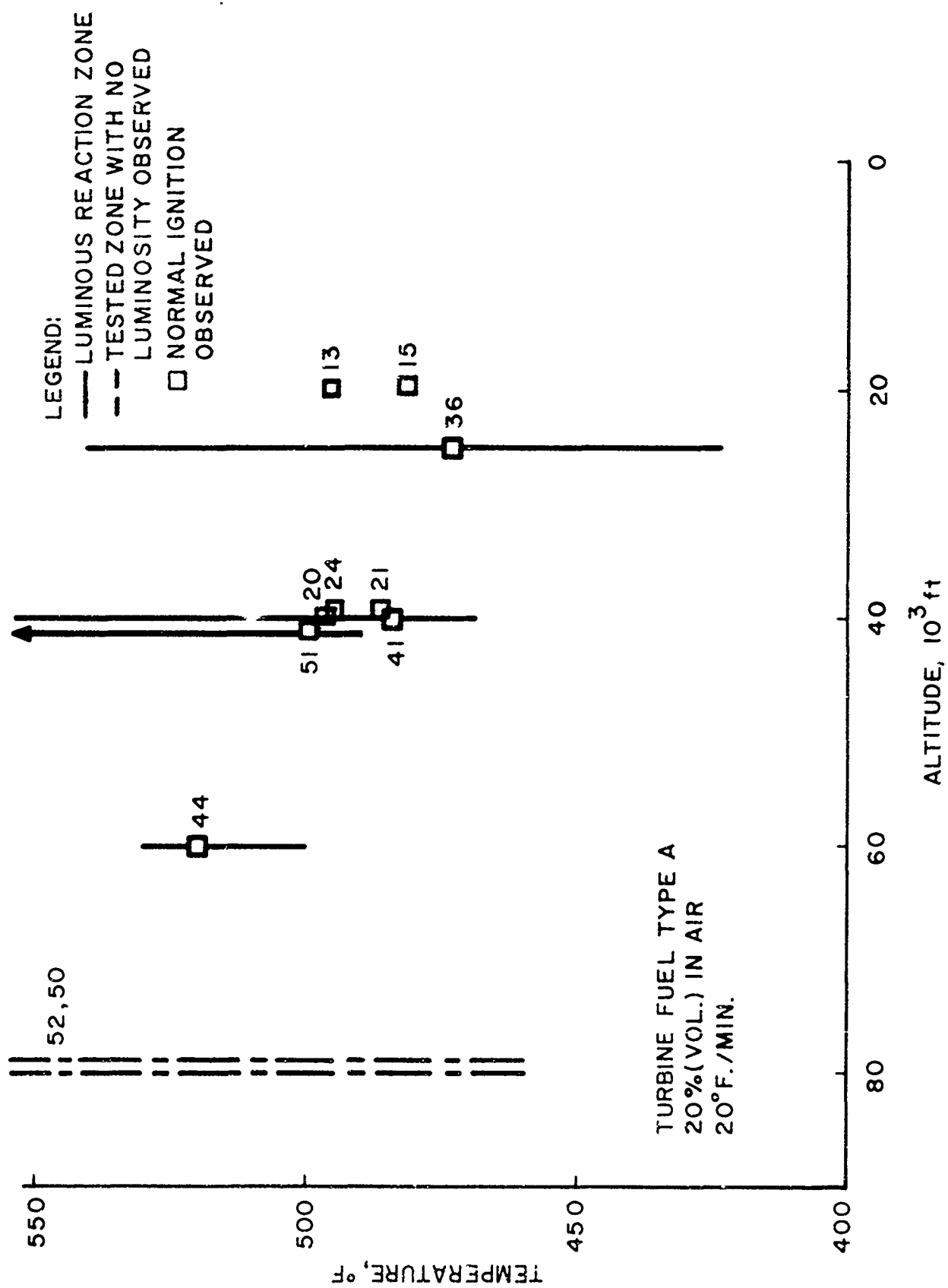
Figure 7.   Ignition Temperatures for 20% TFA in Air.
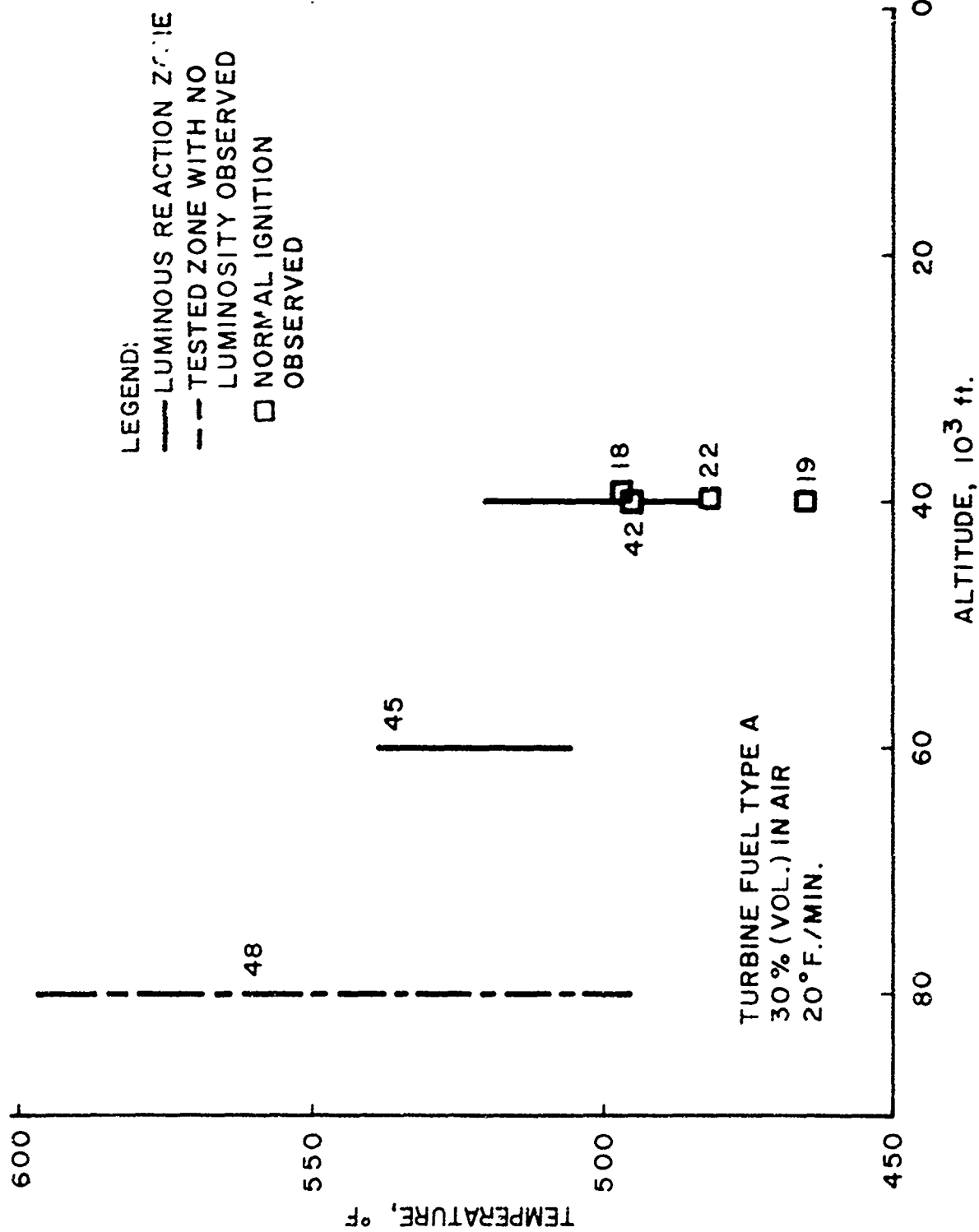
Figure 8. Ignition Temperatures for 30% TFA in Air.
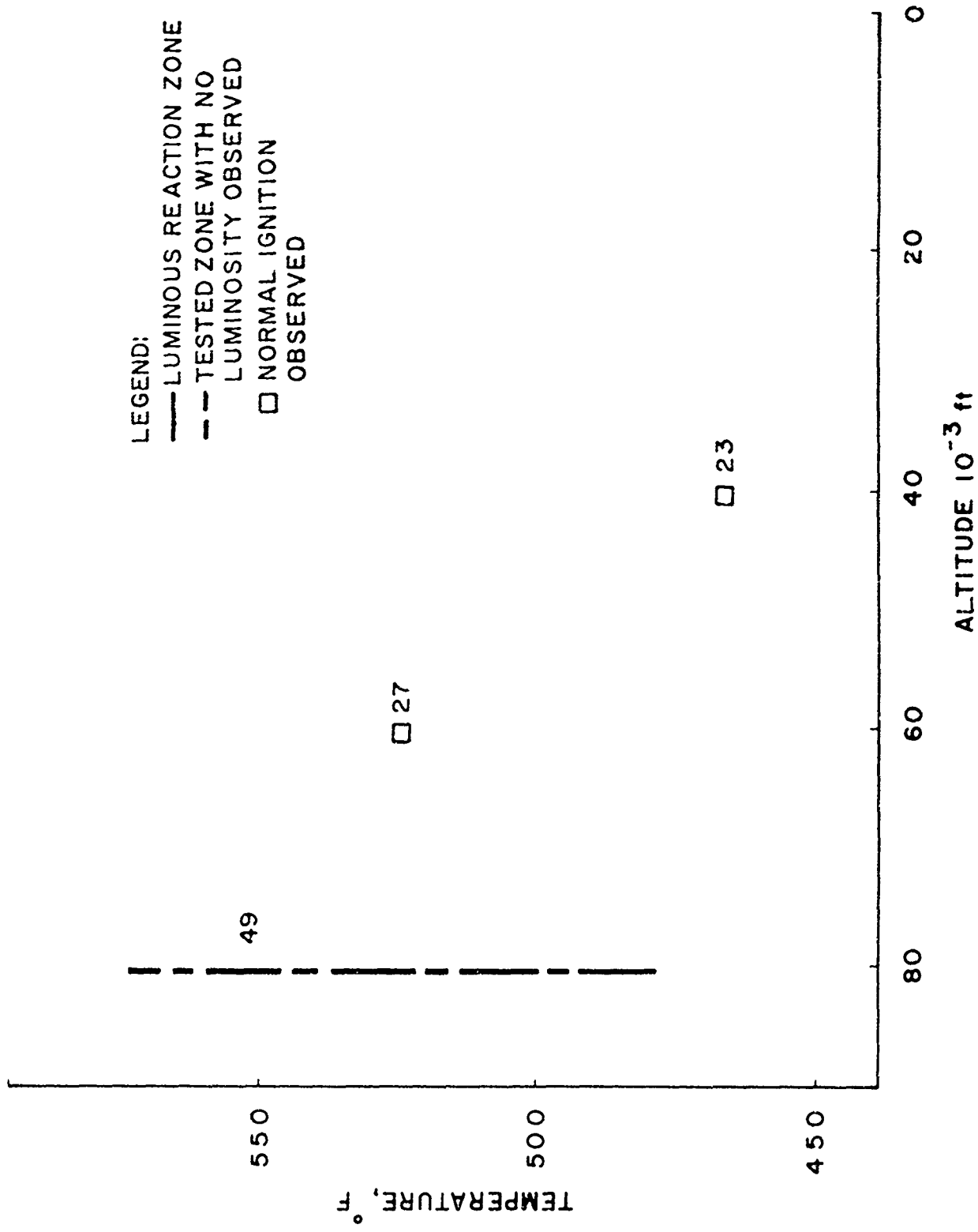
Figure 9.   Ignition Temperatures for 40% TFA in Air.
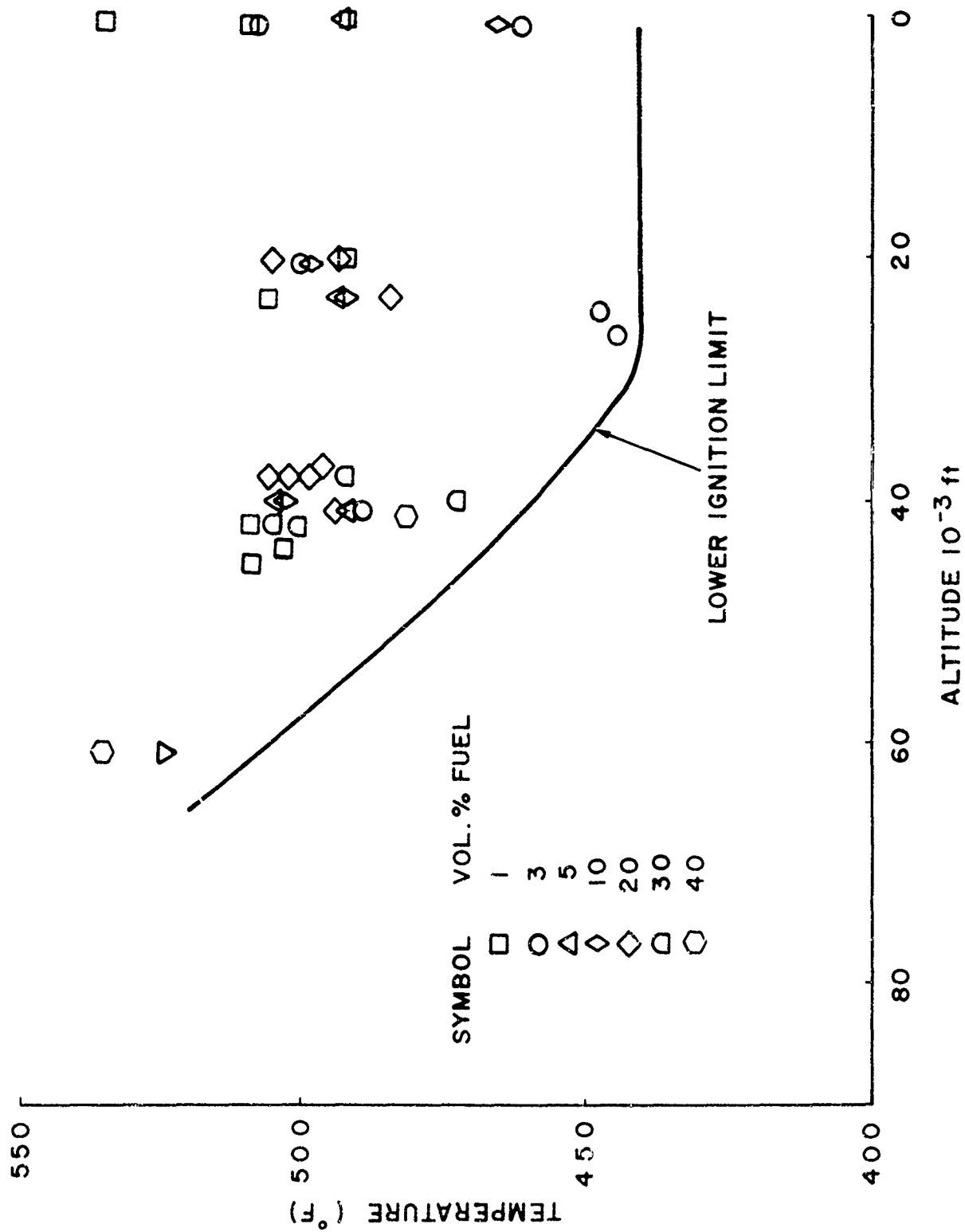
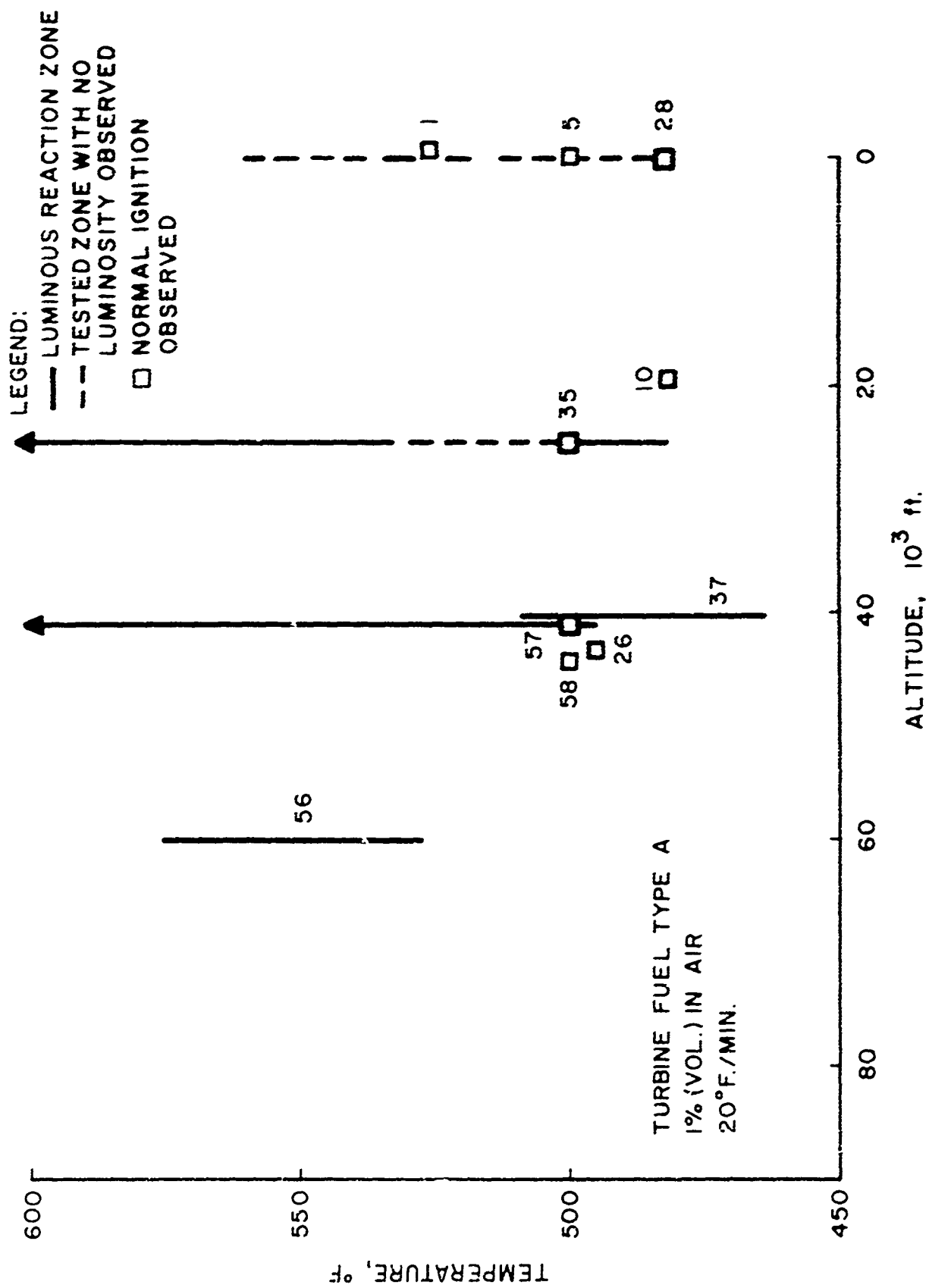Figure 10. Summary of TFA Fuel/Air Ignition Tests.

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NOTE: THESE CURVES WERE OBTAINED BY PLOTTING
ALL THE DATA OF TABLE VI.
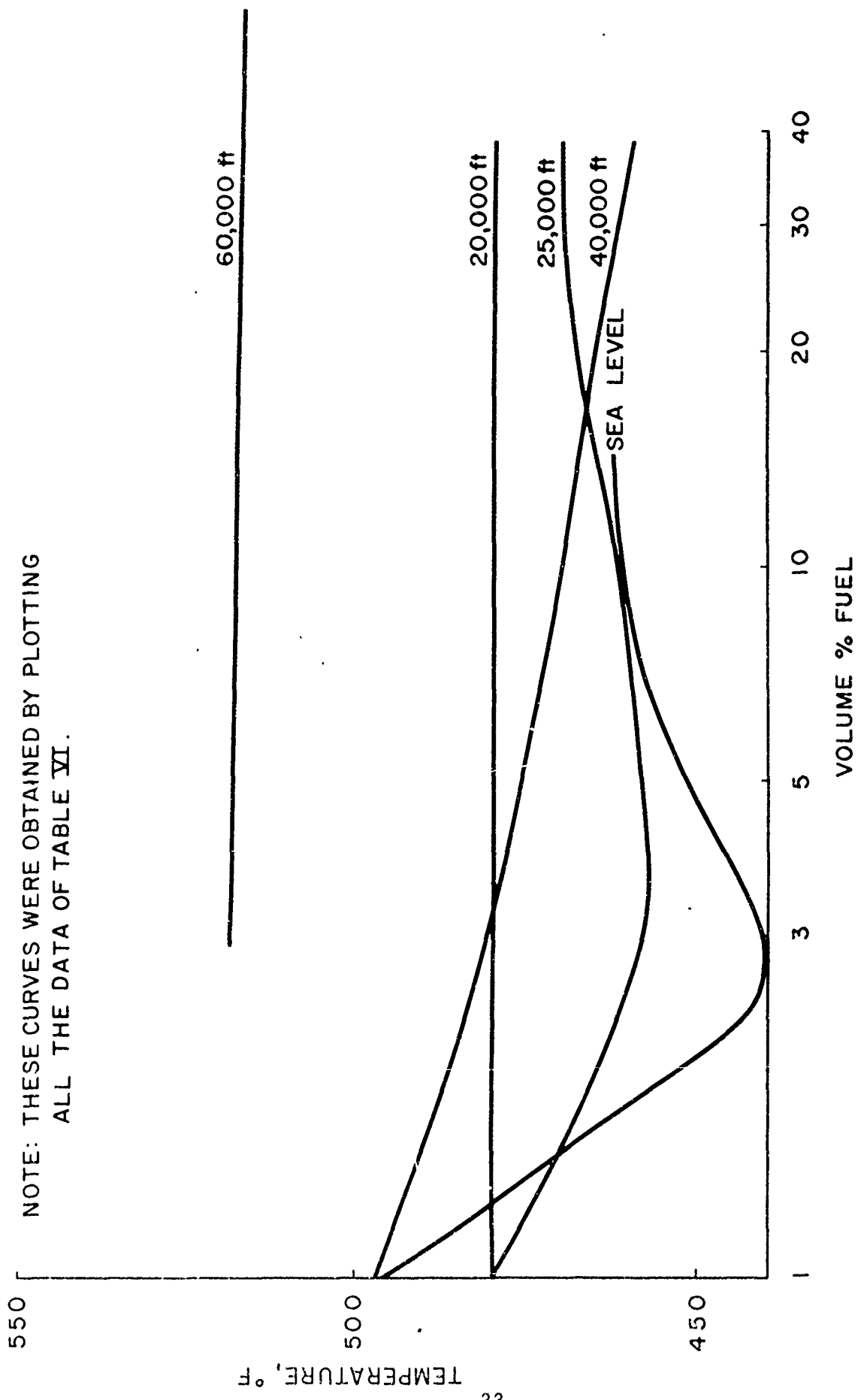
Figure 11.   Lower Ignition Limits for TFA/Air Mixtures at
Various Simulated Altitudes.
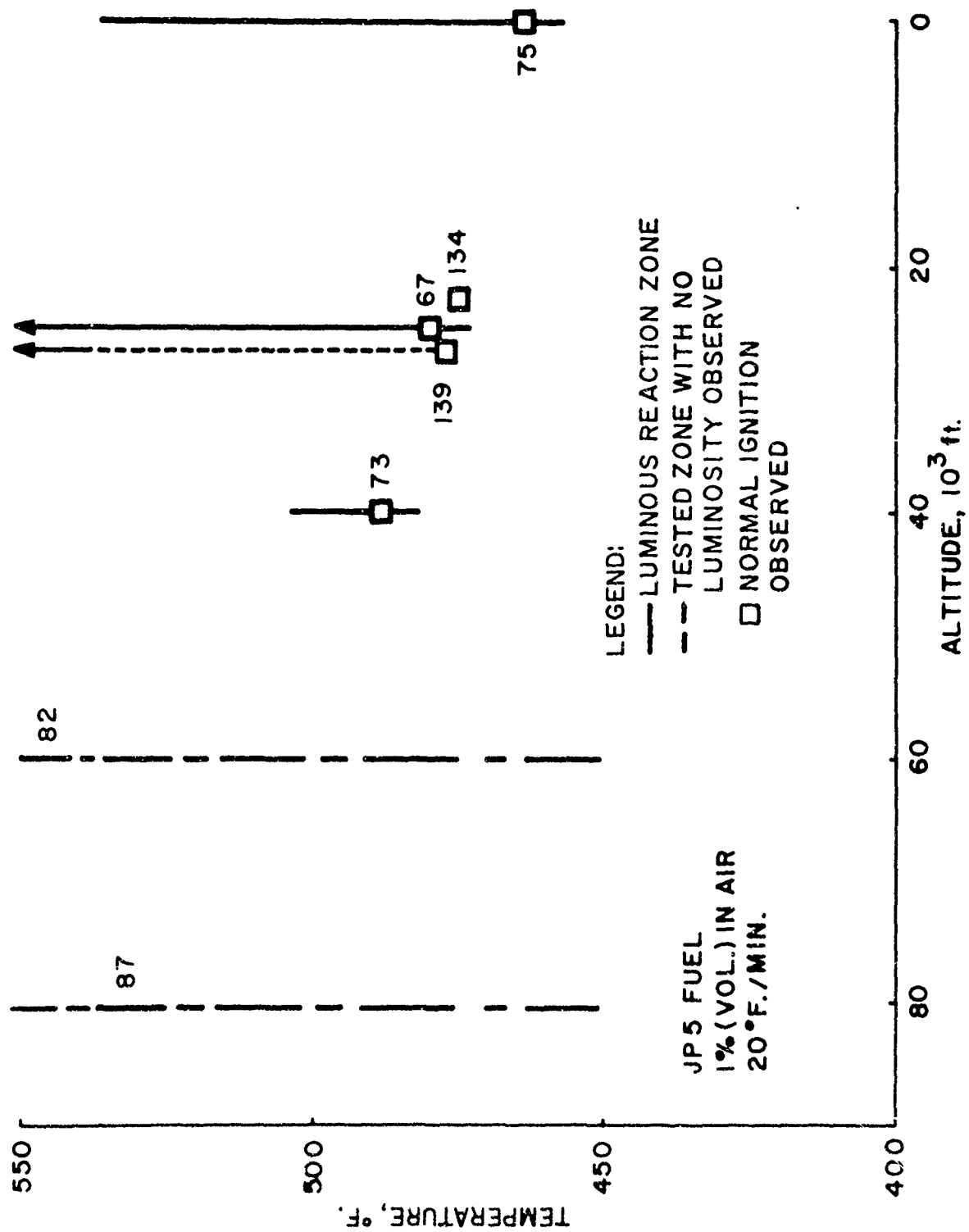
Figure 12. Ignition Temperatures for 1% JP-5 in Air.

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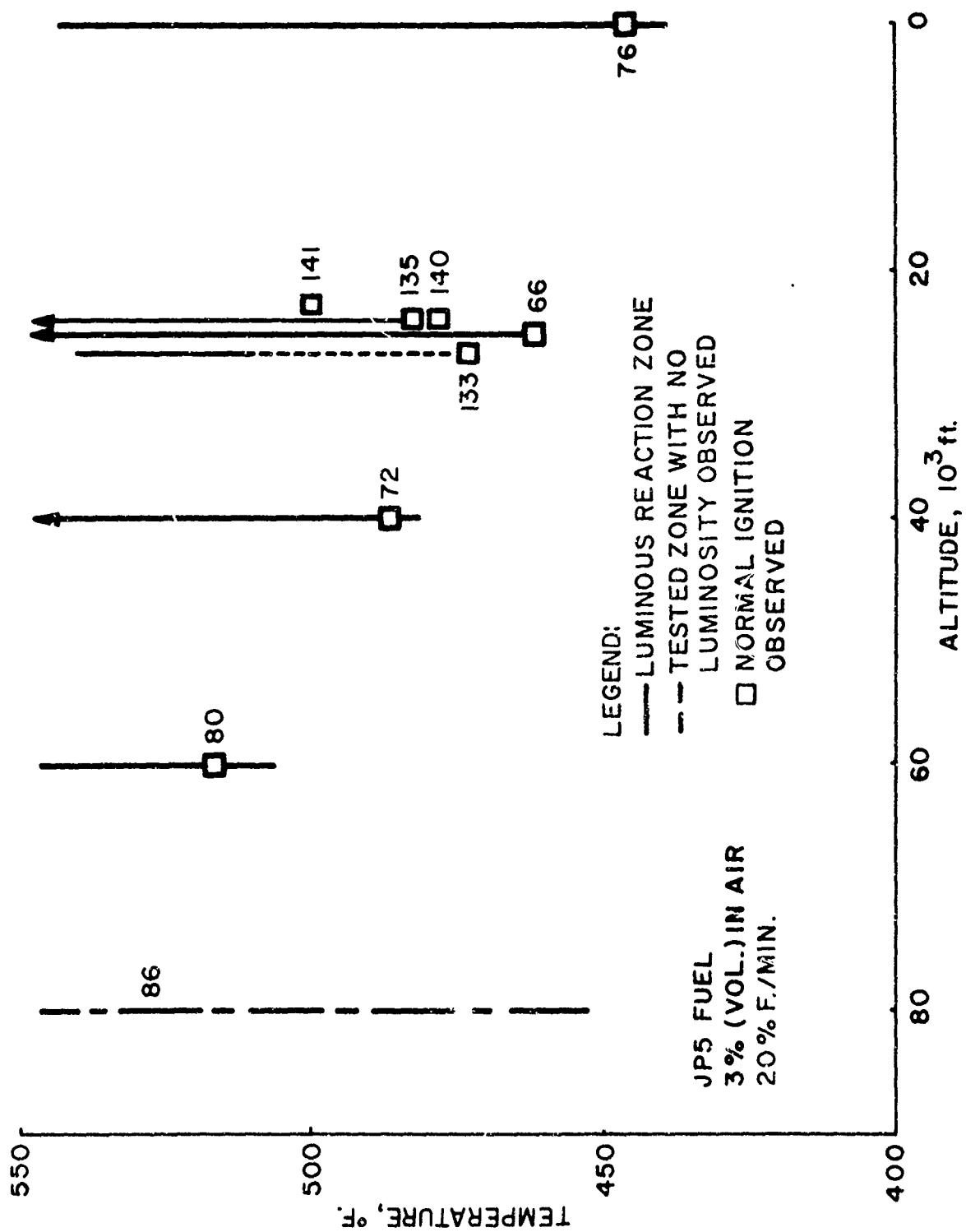
Figure 15.   Ignition Temperatures for 3% JP-5 in Air.

LEGEND:
— LUMINOUS REACTION ZONE
—— TESTED ZONE WITH NO LUMINOSITY OBSERVED
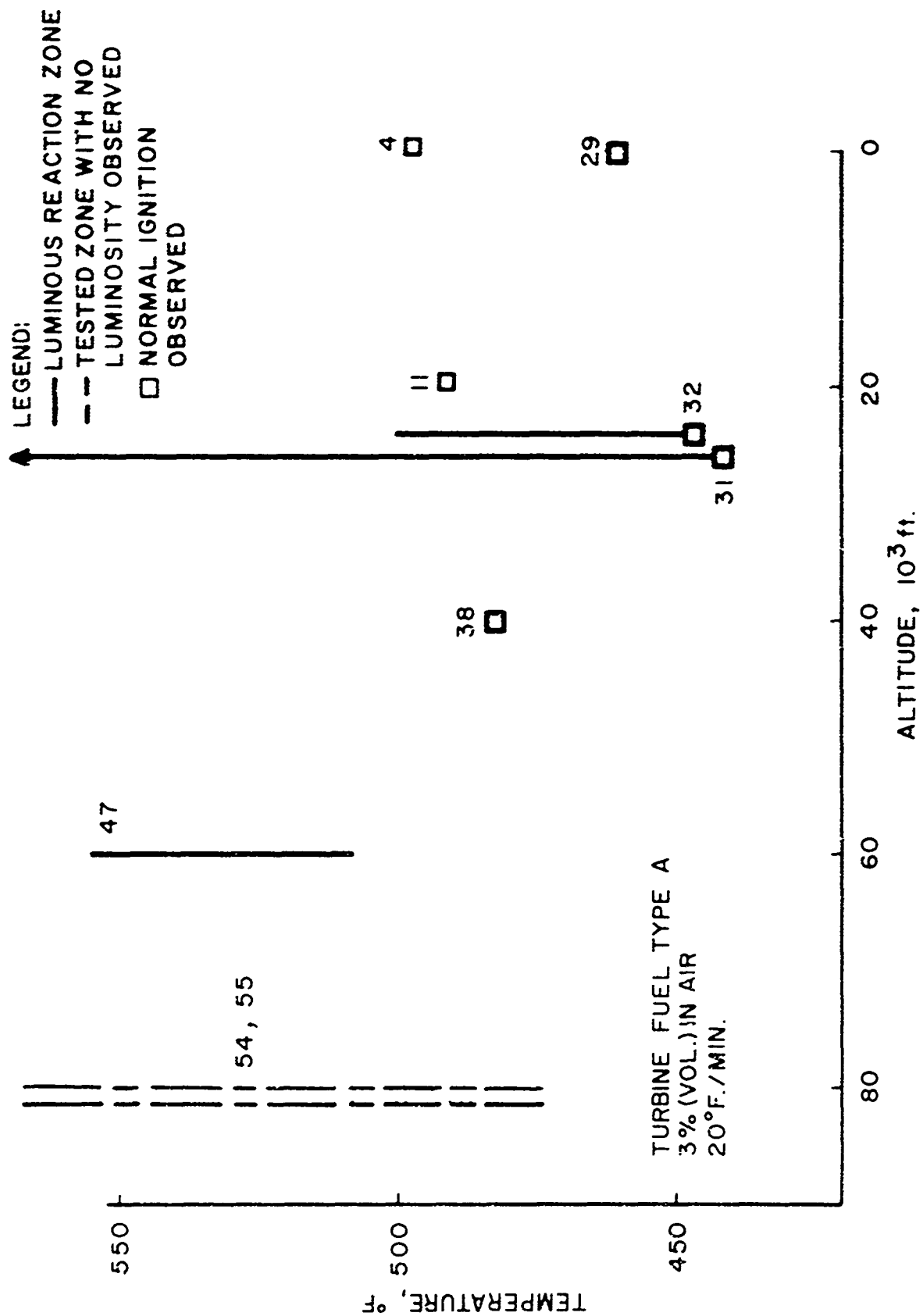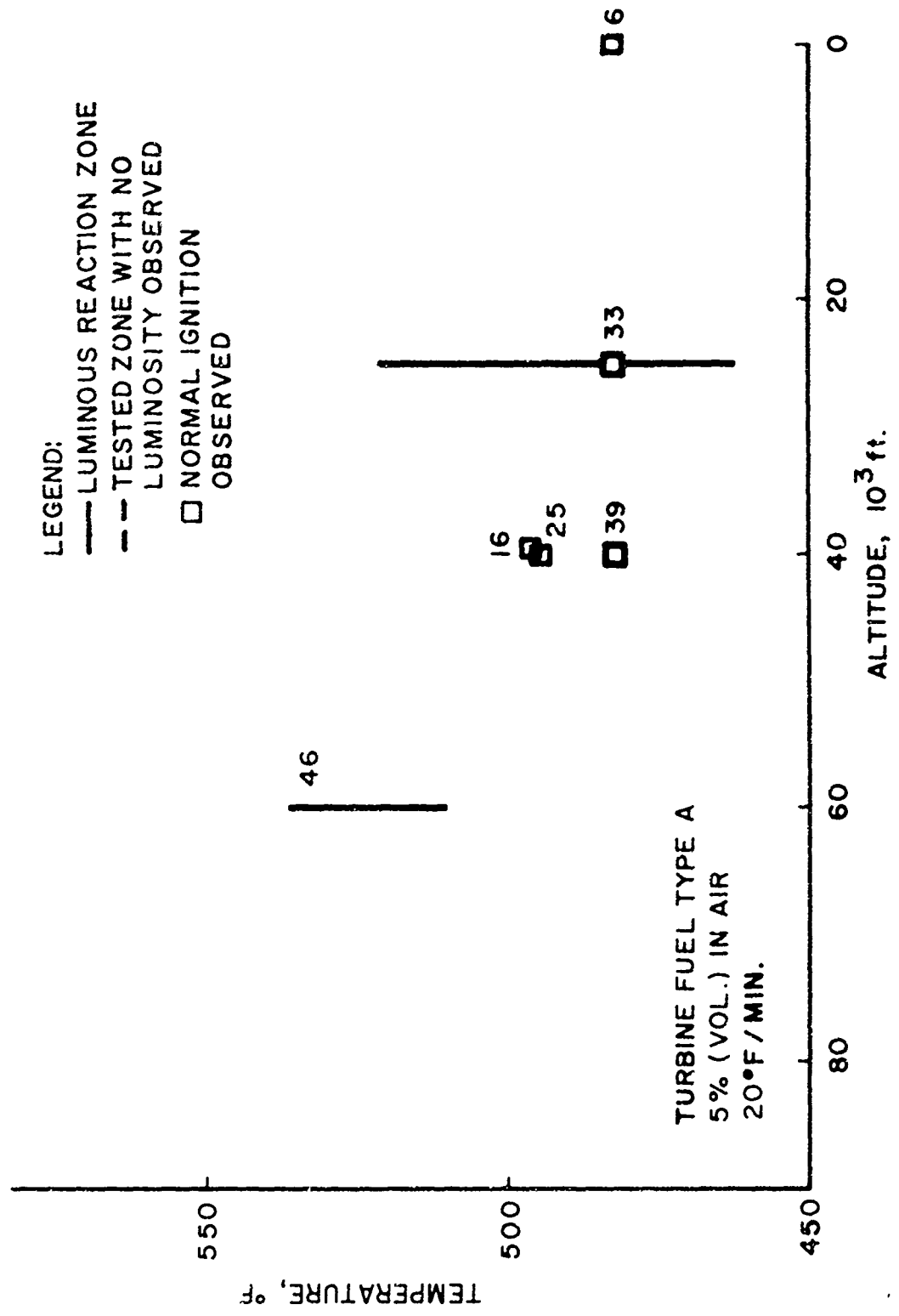□ NORMAL IGNITION OBSERVED

JP5 FUEL
3% (VOL.) IN AIR
20% F./MIN.

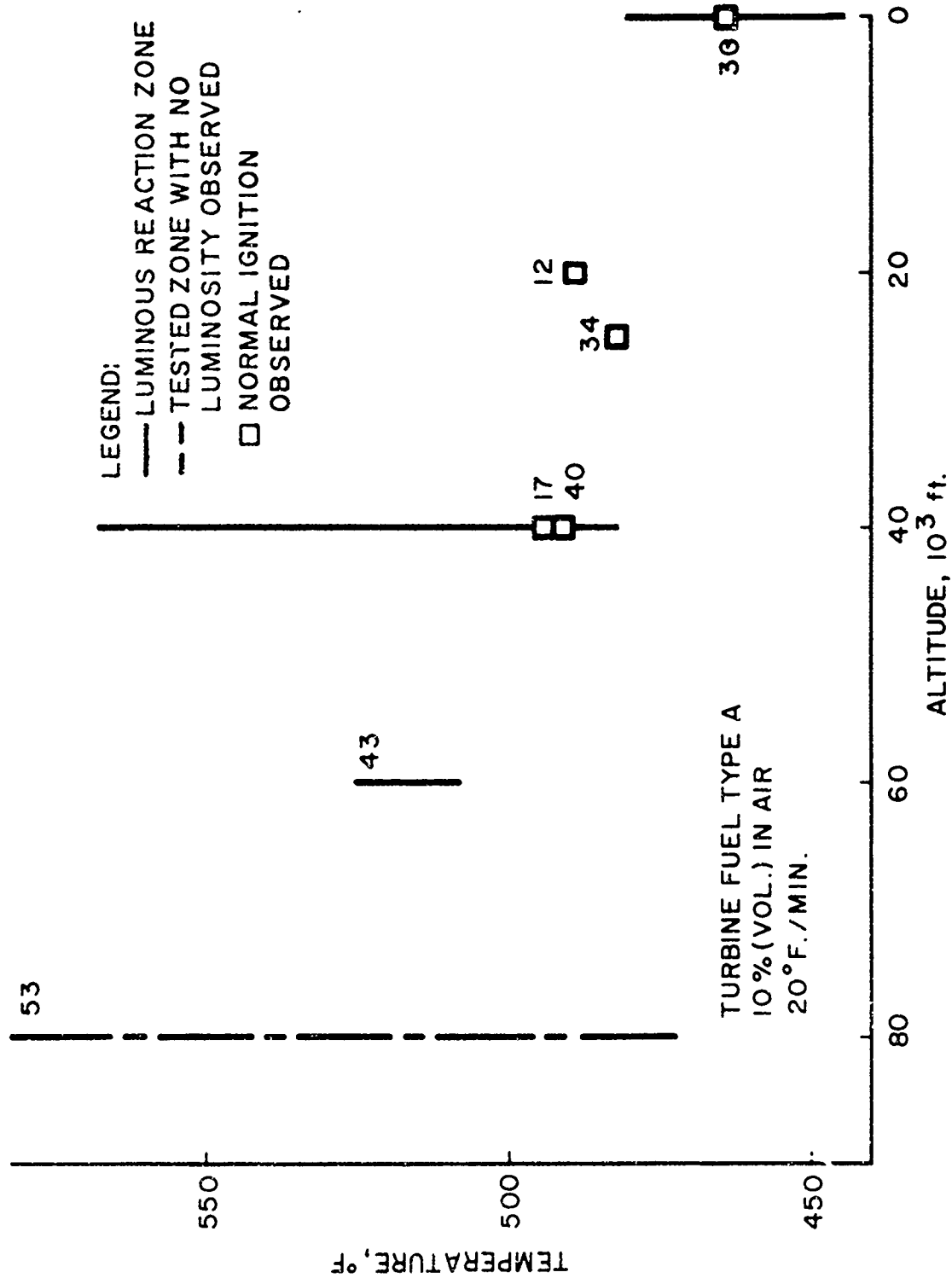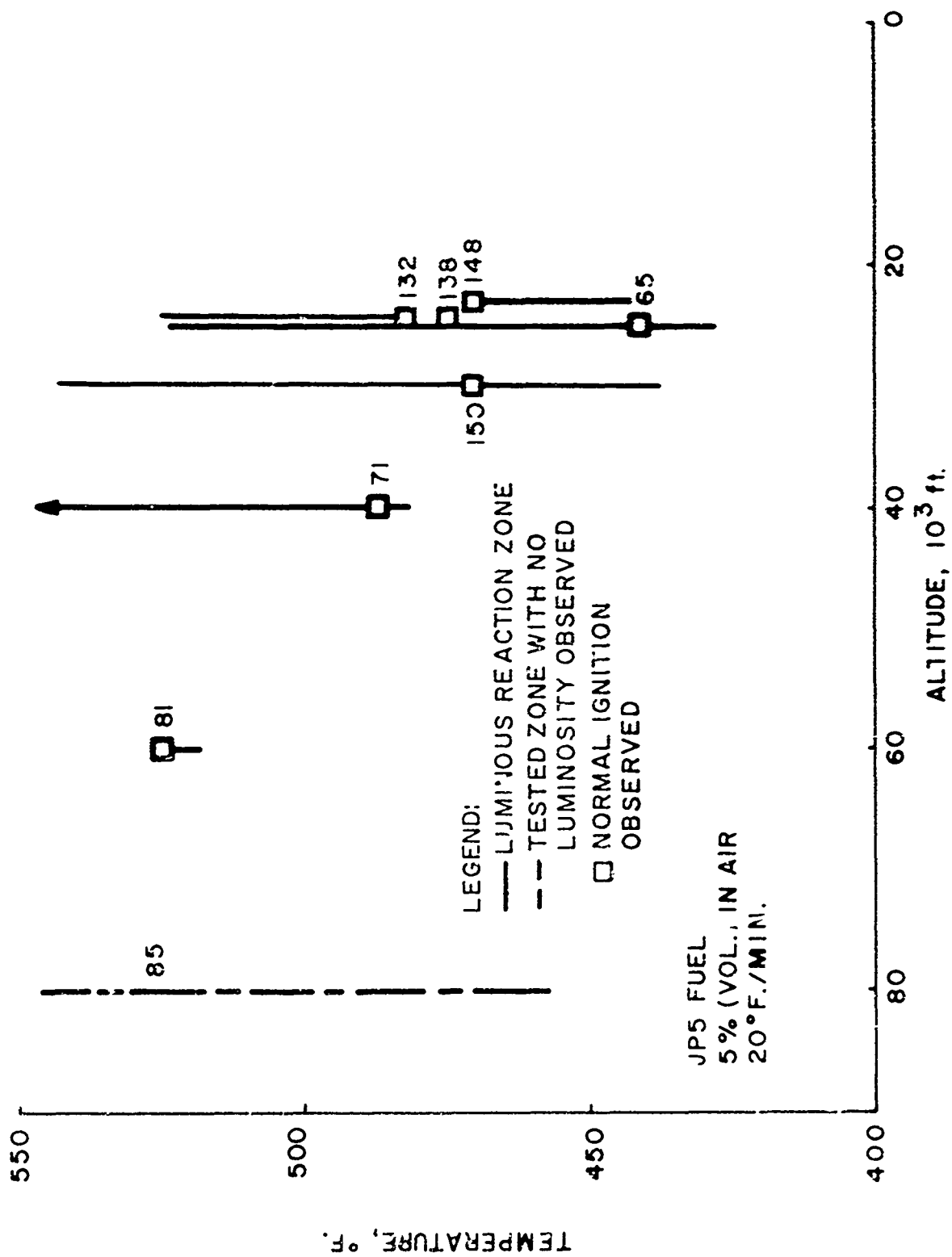Figure 14.   Ignition Temperatures for 5% JP-5 in Air.
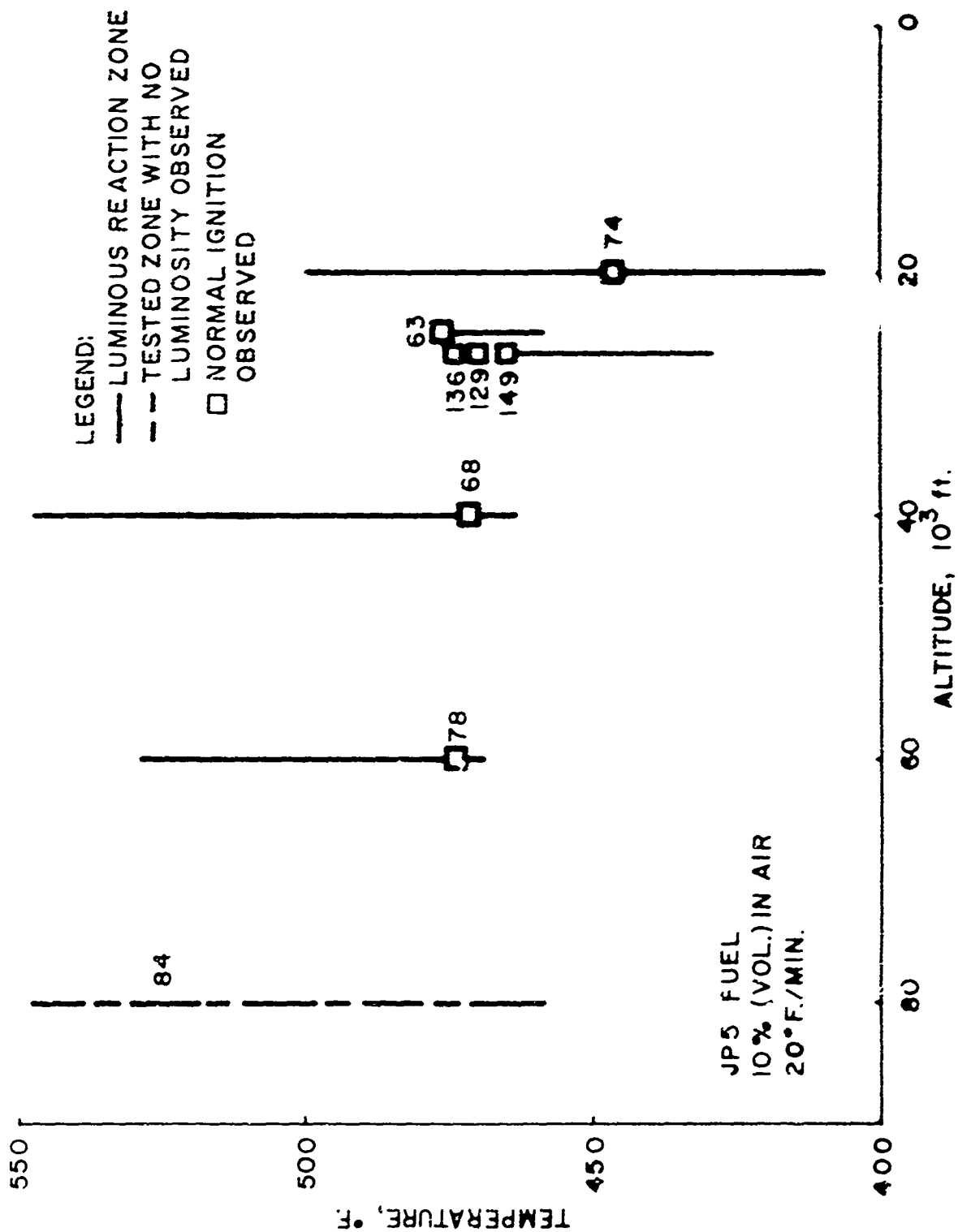
Figure 15. Ignition Temperatures for 10% JP-5 in Air
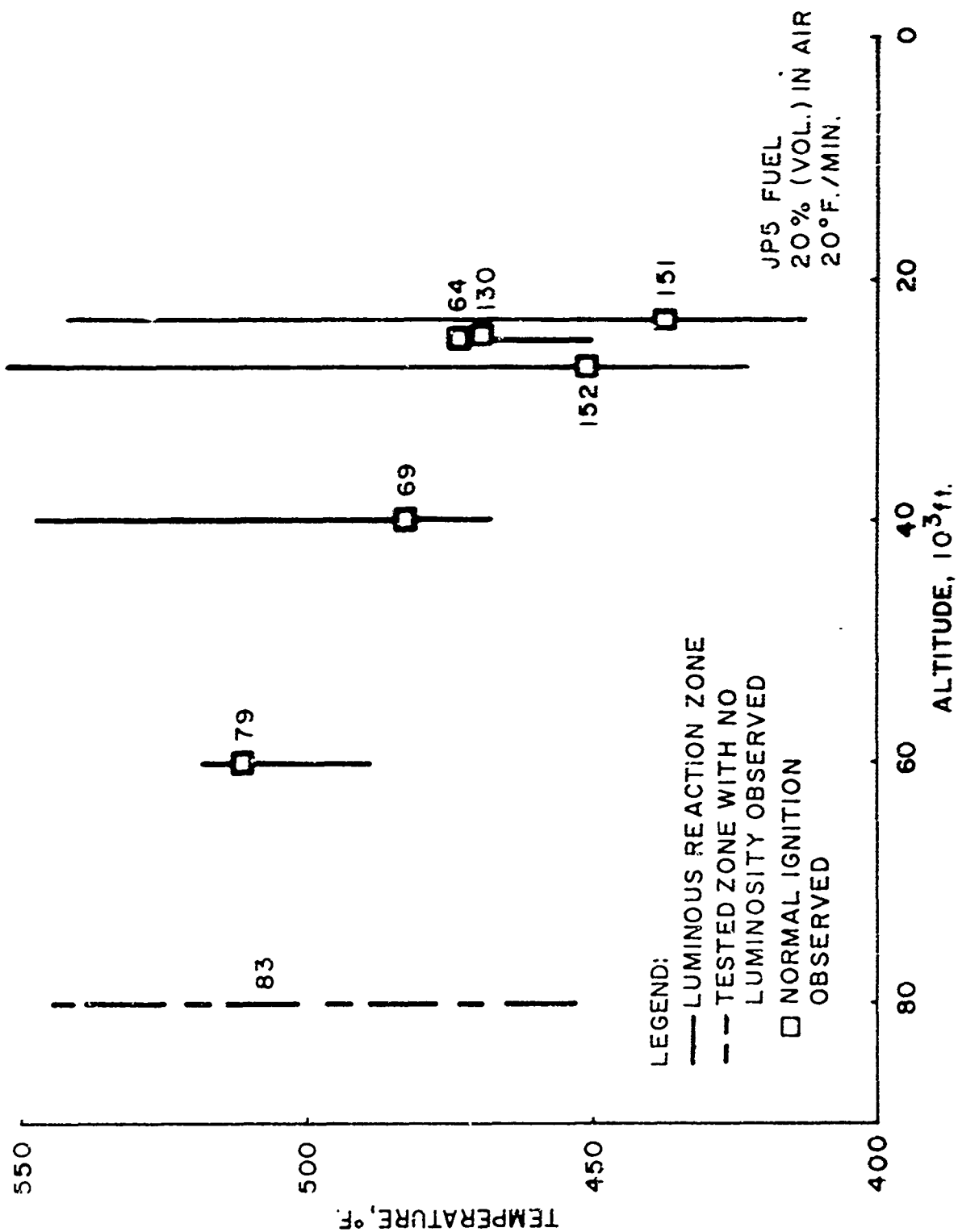
Figure 16. Ignition Temperatures for 20% JP-5 in Air.
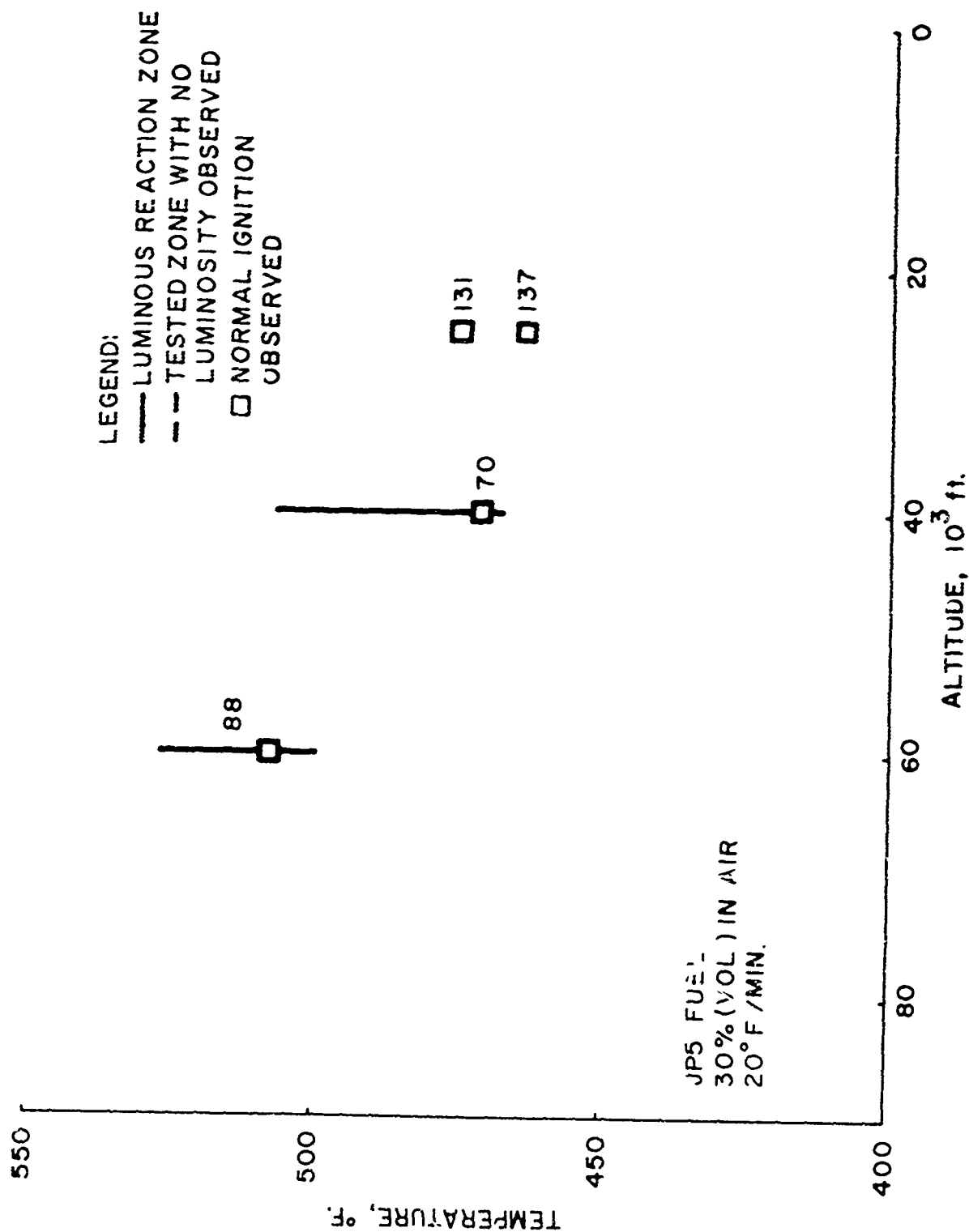
Figure 17.   Ignition Temperatures for 30% JP-5 in Air.
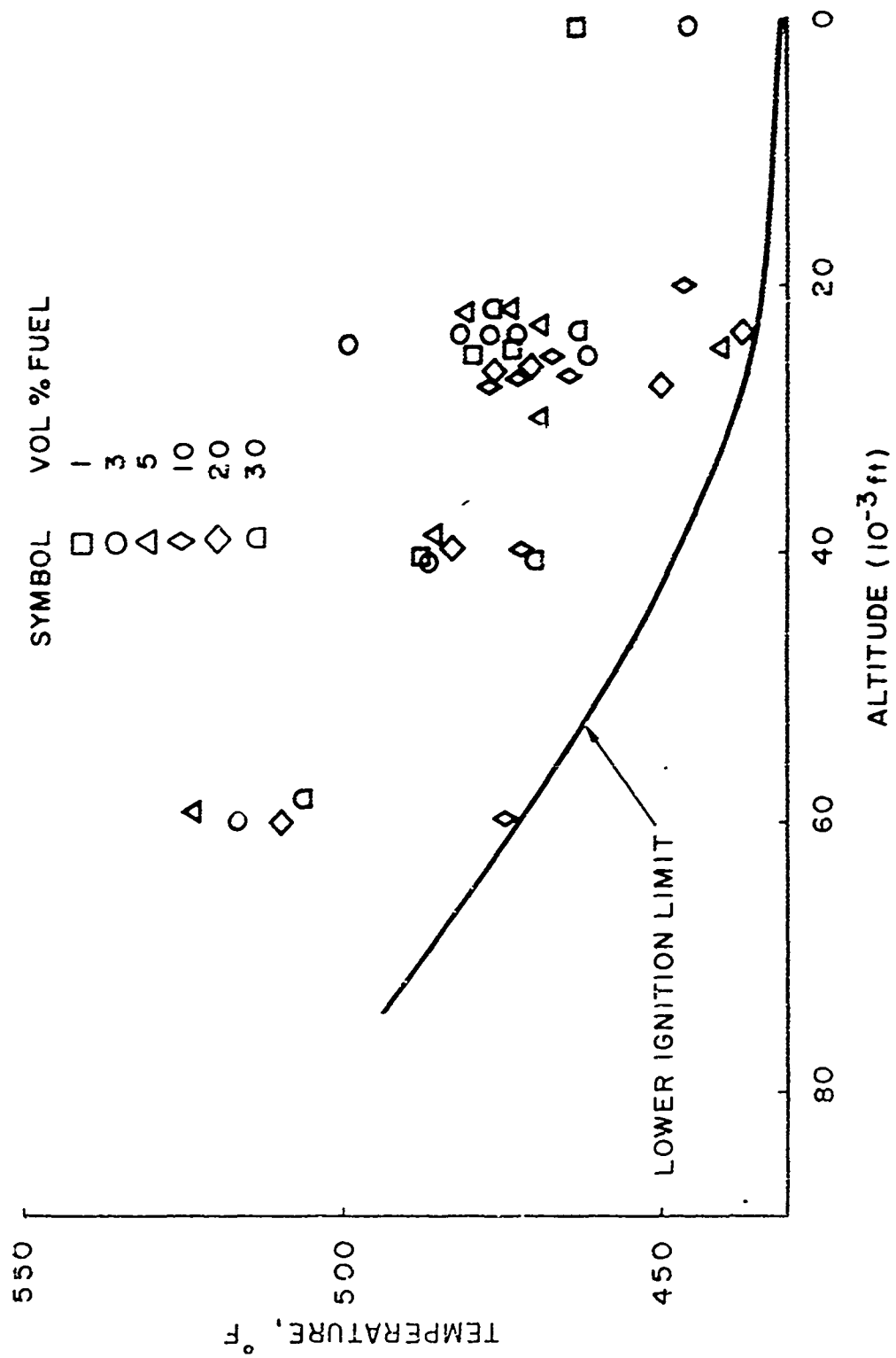
Figure 18.   Summary of JP-5 Fuel/Air Ignition Tests.

NOTE: THESE CURVES WERE OBTAINED BY PLOTTING
ALL THE DATA OF TABLE VII.
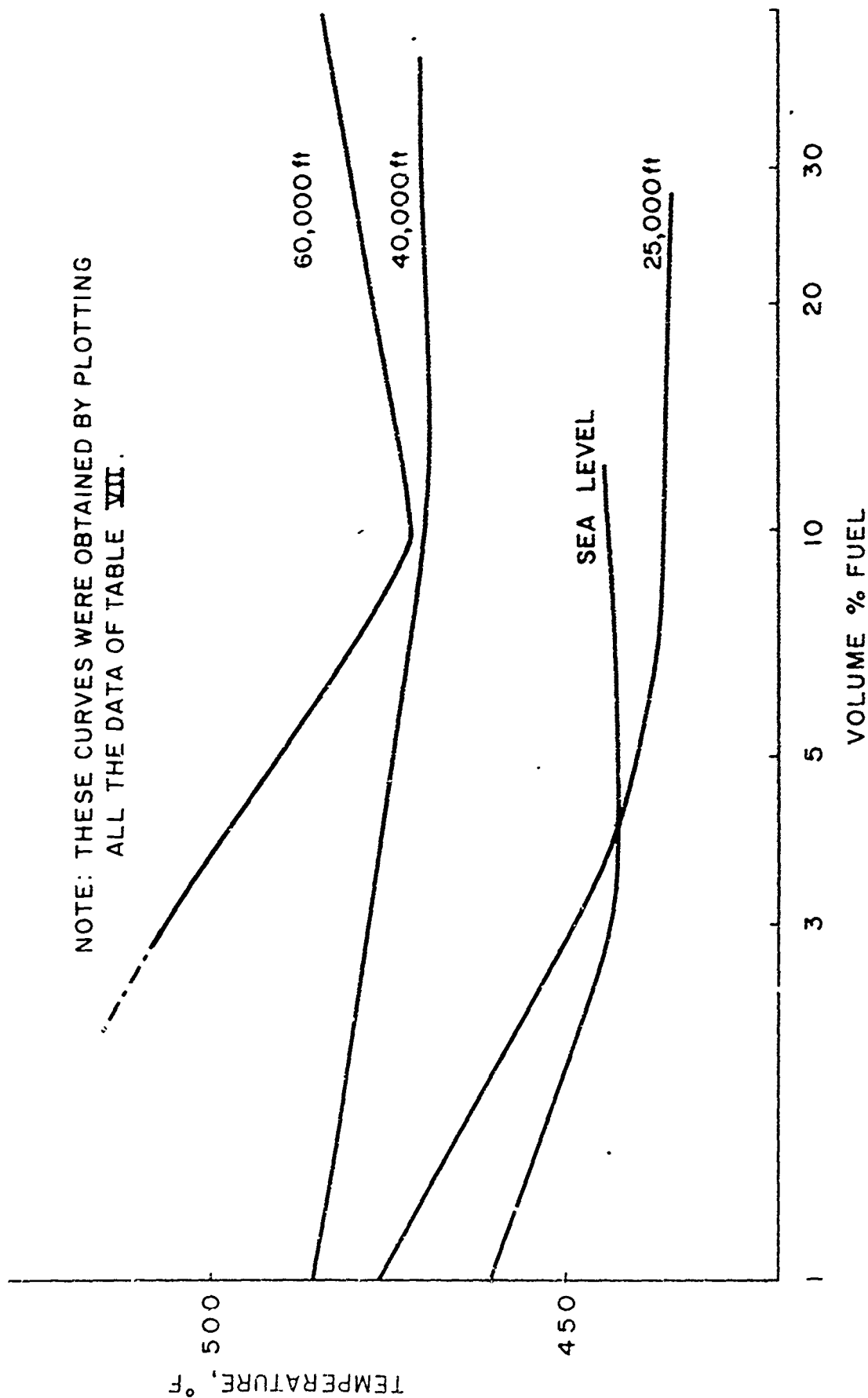
Figure 19.   Lower Ignition Limits for JP-5 Fuel/Air Mixtures at Various
Simulated Altitudes.

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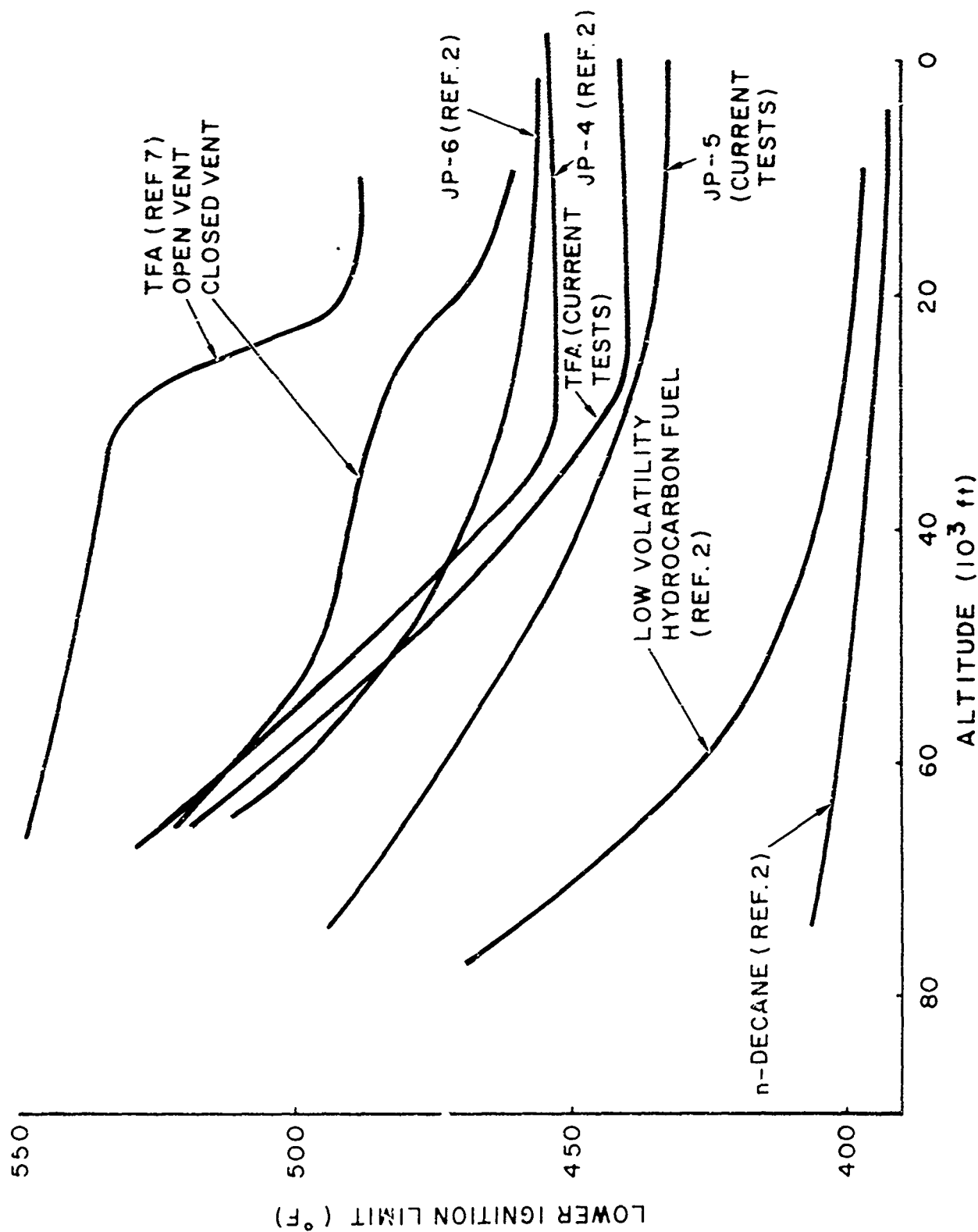
Figure 20. Comparison of Lower Limits for Various Fuels as Measured for a Range of Compositions

42

Variable Diffusion Times

Fuel Injected as Liquid

Evaporation and Diffusion

Rich Mixtures

5ft.

Lean Mixtures

Mild Steel

2ft.

4in
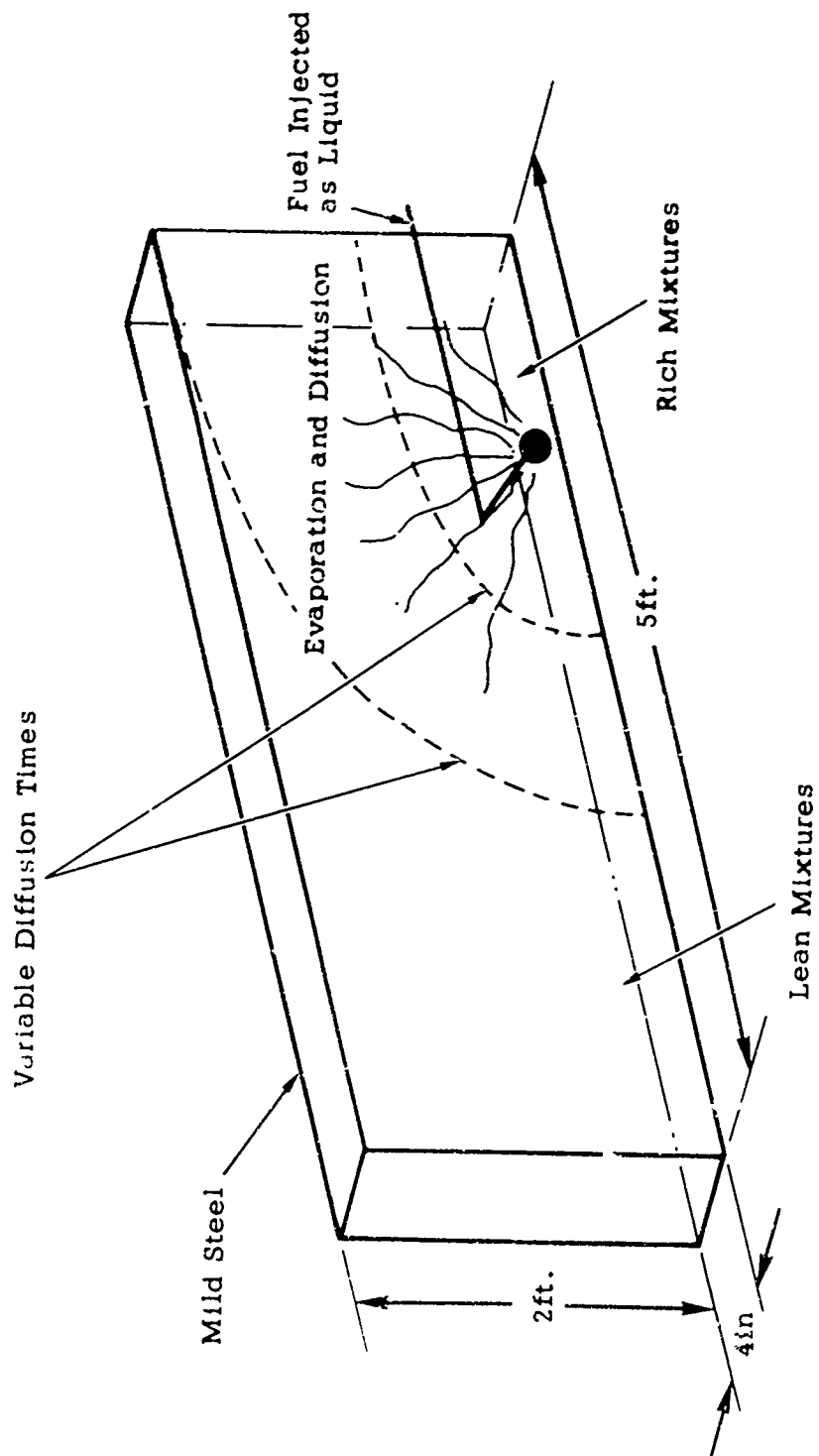
Figure 21. Schematic Diagram of Lockheed Dry Test Bay Showing How Diffusion of Fuel Vapors May Lead to Non-Uniform Fuel/Air Mixtures
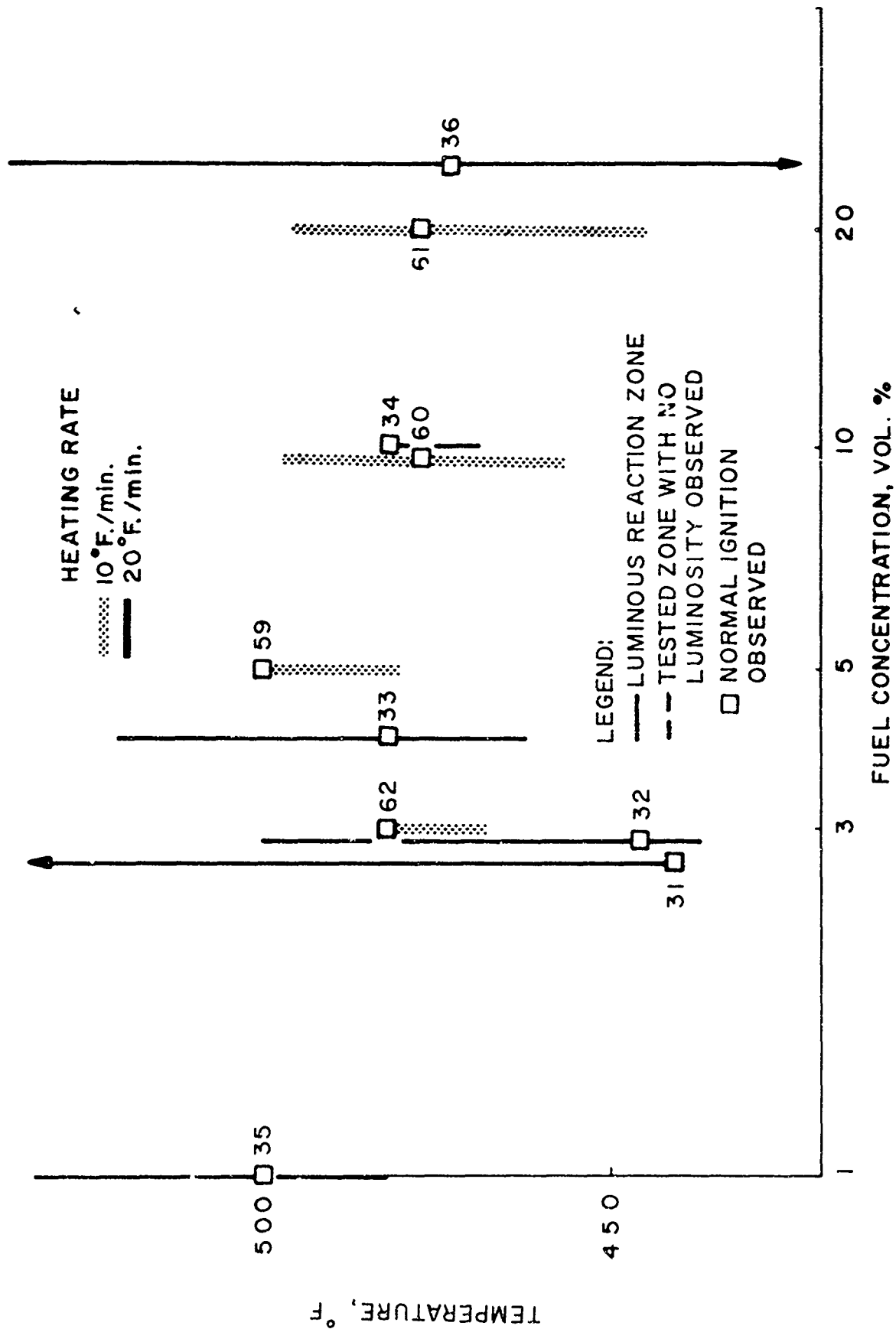
Figure 22. Comparison of Measured Ignition Temperatures for Heating Rates of 10 and 20°F/min. (TFA data from Table VIII).

44
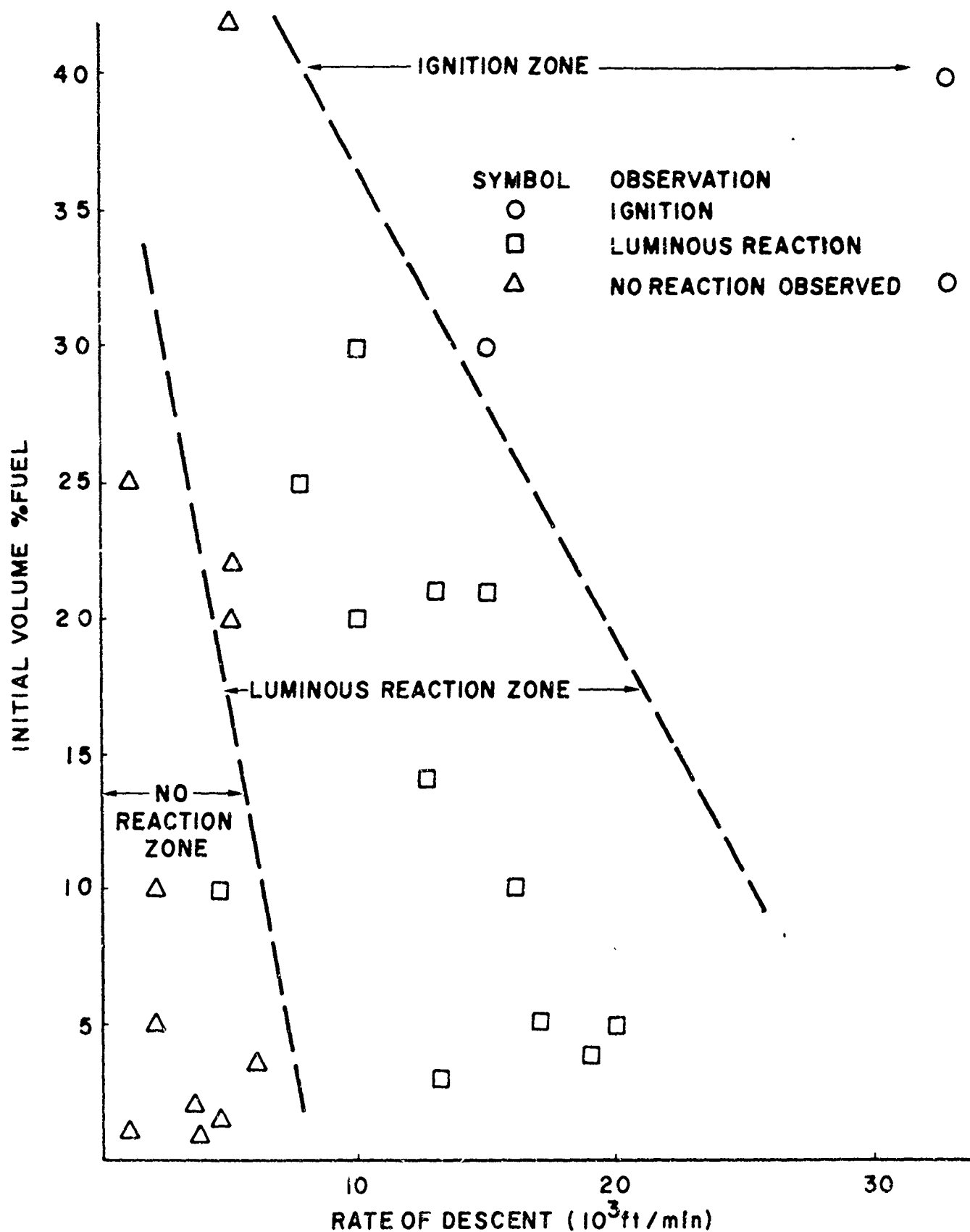
Figure 23.   Zones of Reaction for Descent Profiles of TFA/Air Mixtures.
Data from Table VI)

45
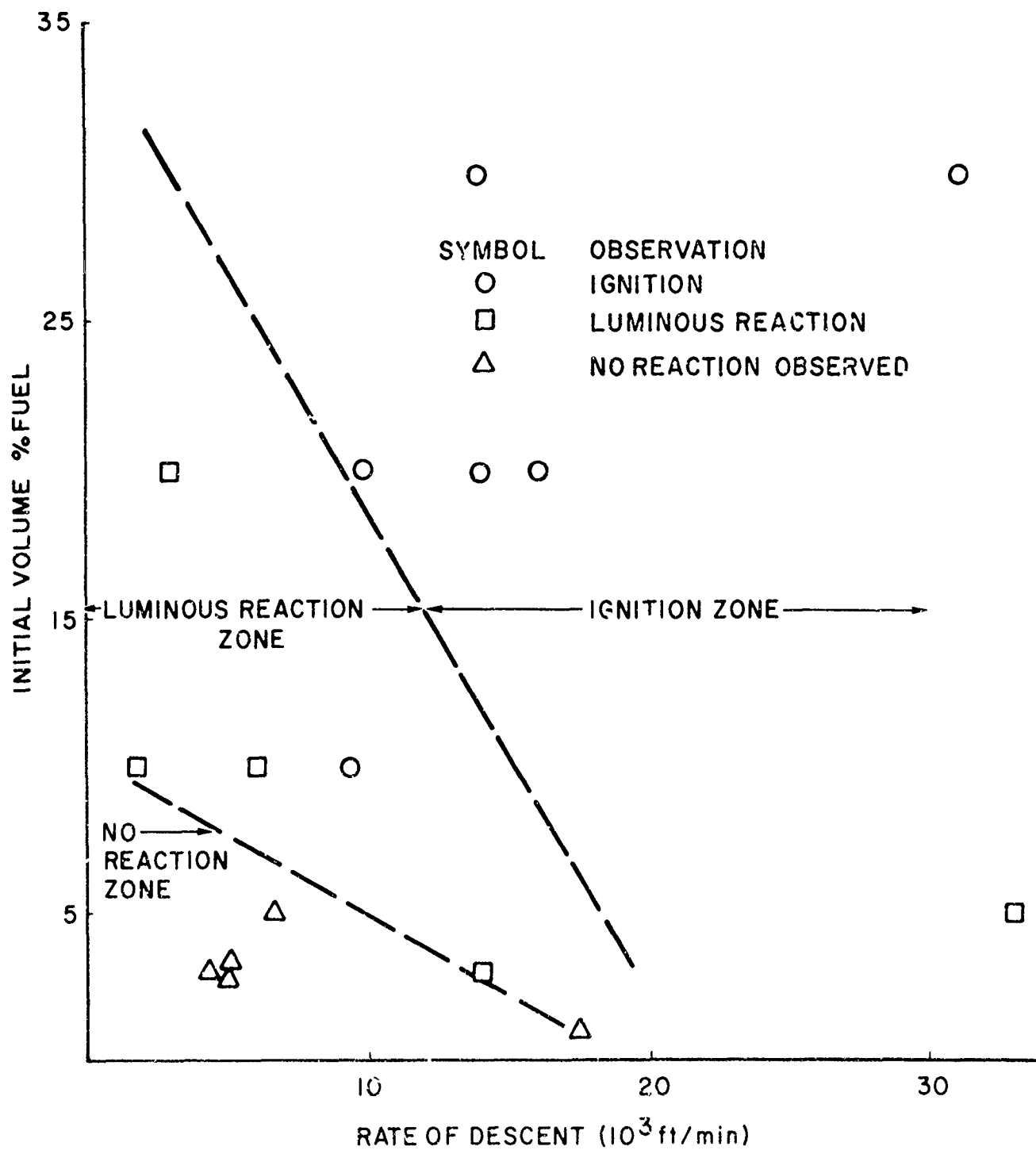
Figure 24.   Zones of Reaction for Descent Profiles of JP-5/Air Mixtures.
(Data from Table VII)
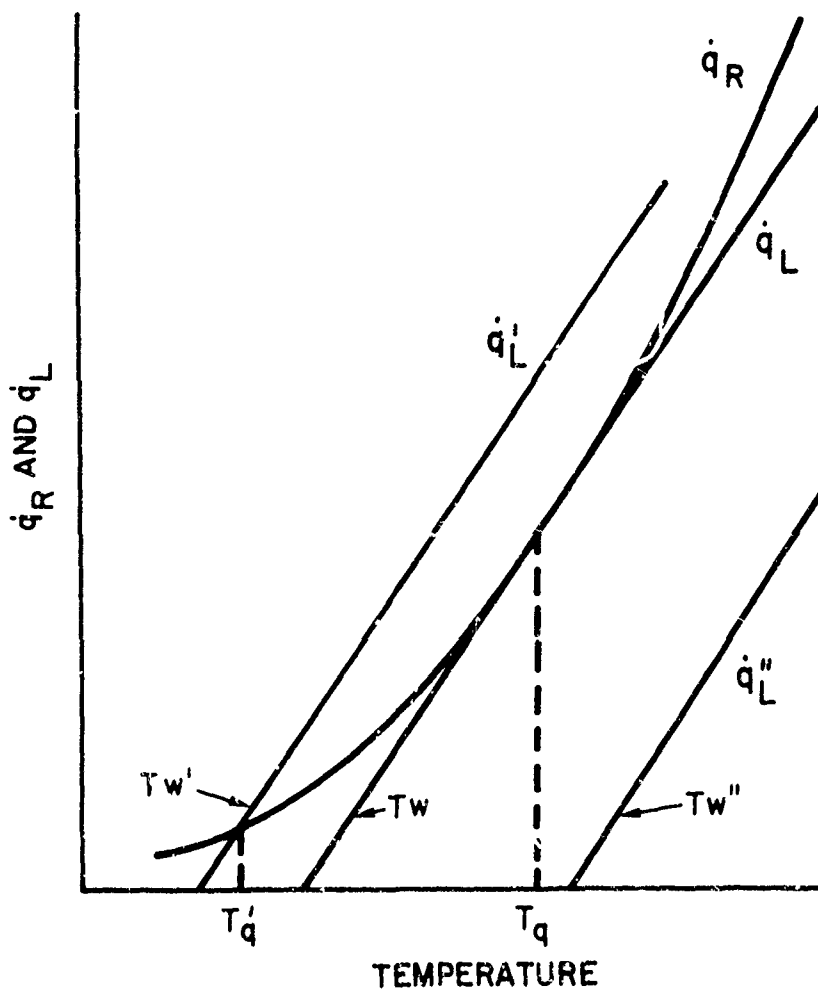
Figure 25.   Relationships of Heat Production Rate, Heat Loss Rate, Gas Temperature, and Wall Temperature.

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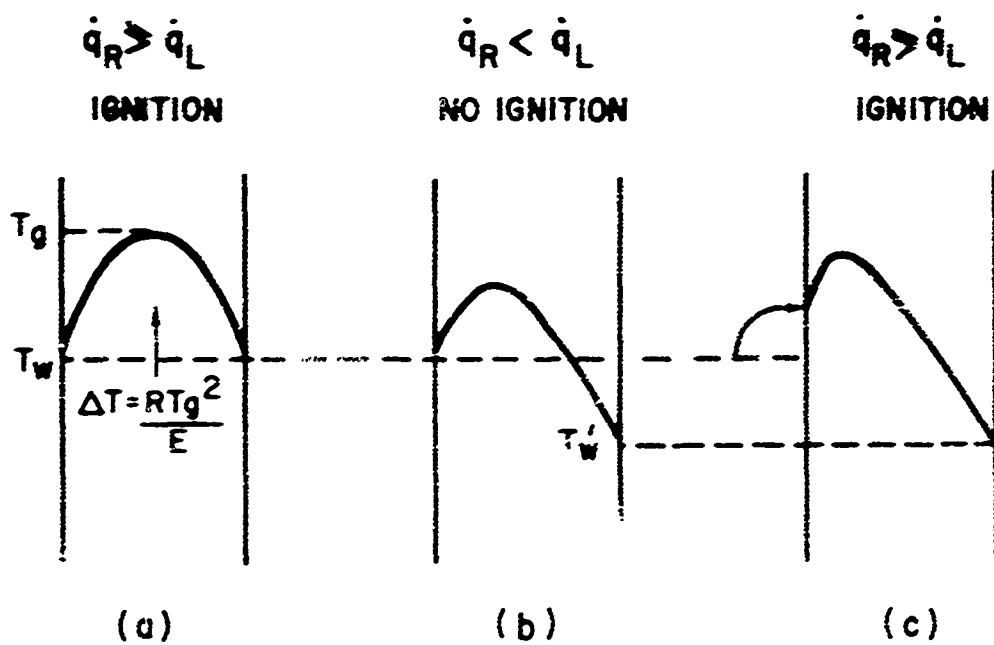
Figure 26. Temperature Profile Across Reactor Showing Effect of Cool Wall.
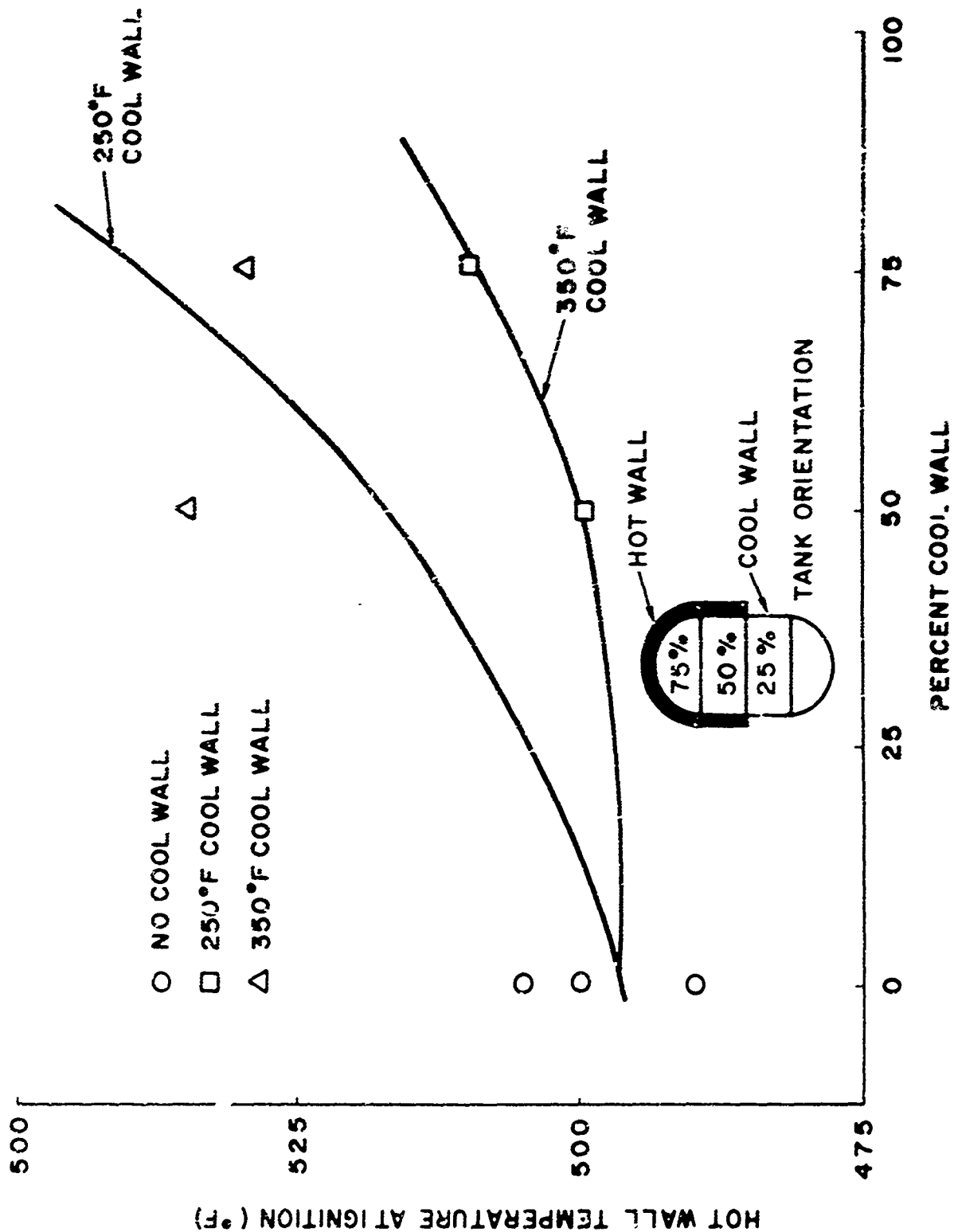
Figure 27. Effect of percentage Cool Wall on Hot Wall Temperatures Required for Ignition. (TFA)

49
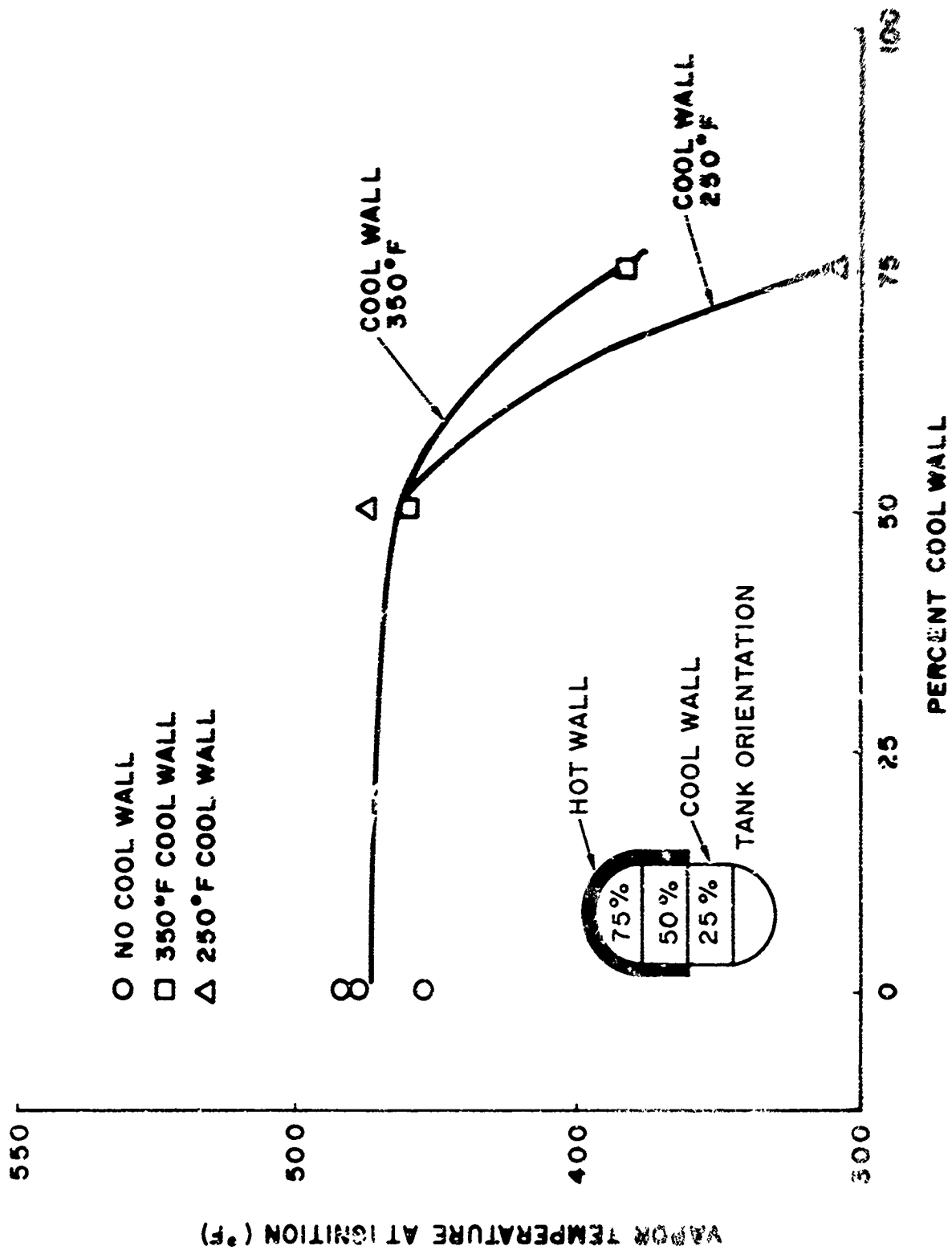
Figure 28. Effect of Presence of a Cool Wall on the Vapor Phase Temperature
(TC_v^1) at Ignition. (TFA)

LEGEND:
—— LUMINOUS REACTION ZONE
—— TESTED ZONE WITH NO
    LUMINOSITY OBSERVED
☐ NORMAL IGNITION
    OBSERVED
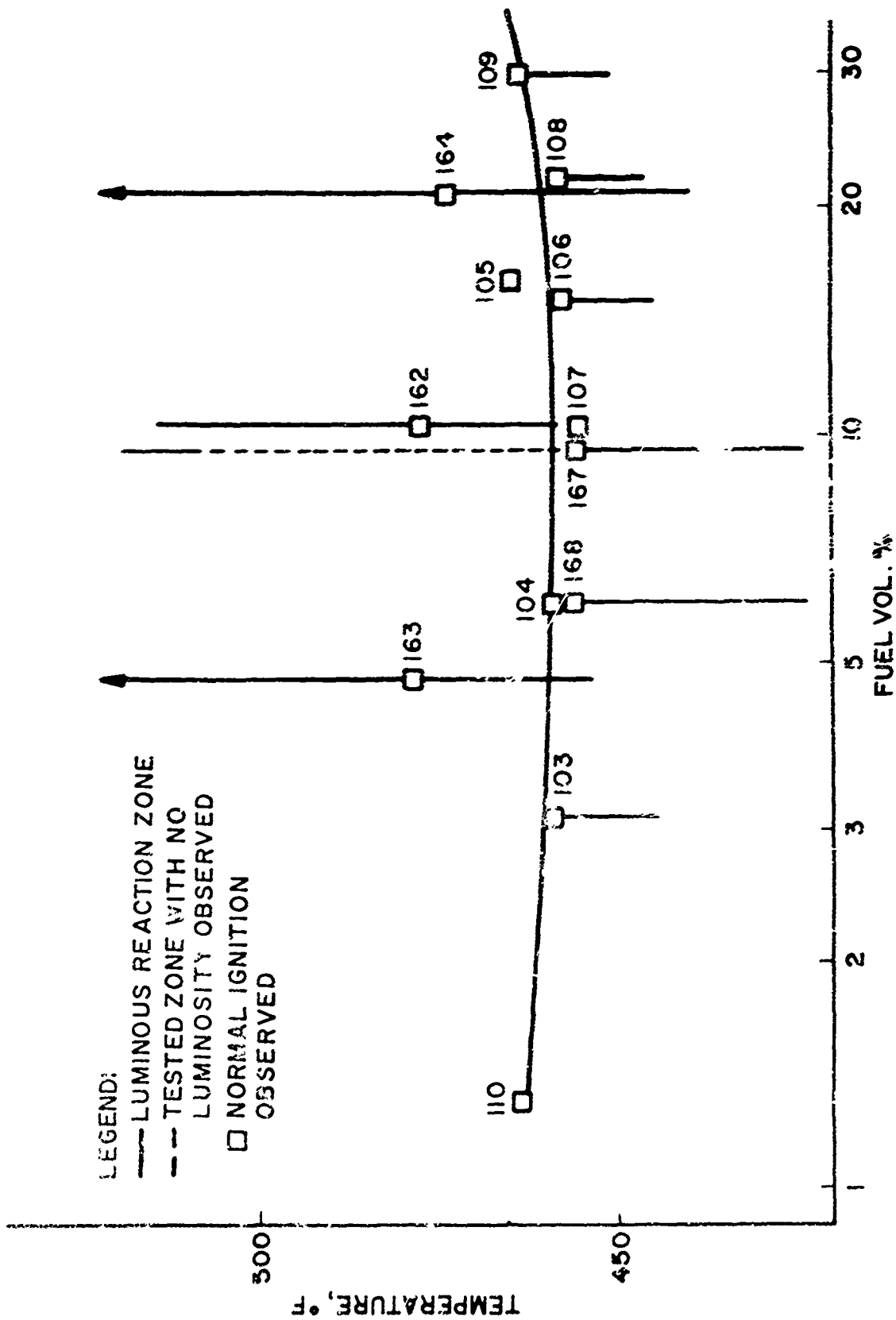
Figure 29. Effect of Metal Deactivator on Ignition of JF-5/Air Mixtures at 25,000 feet Altitude. (Table X)
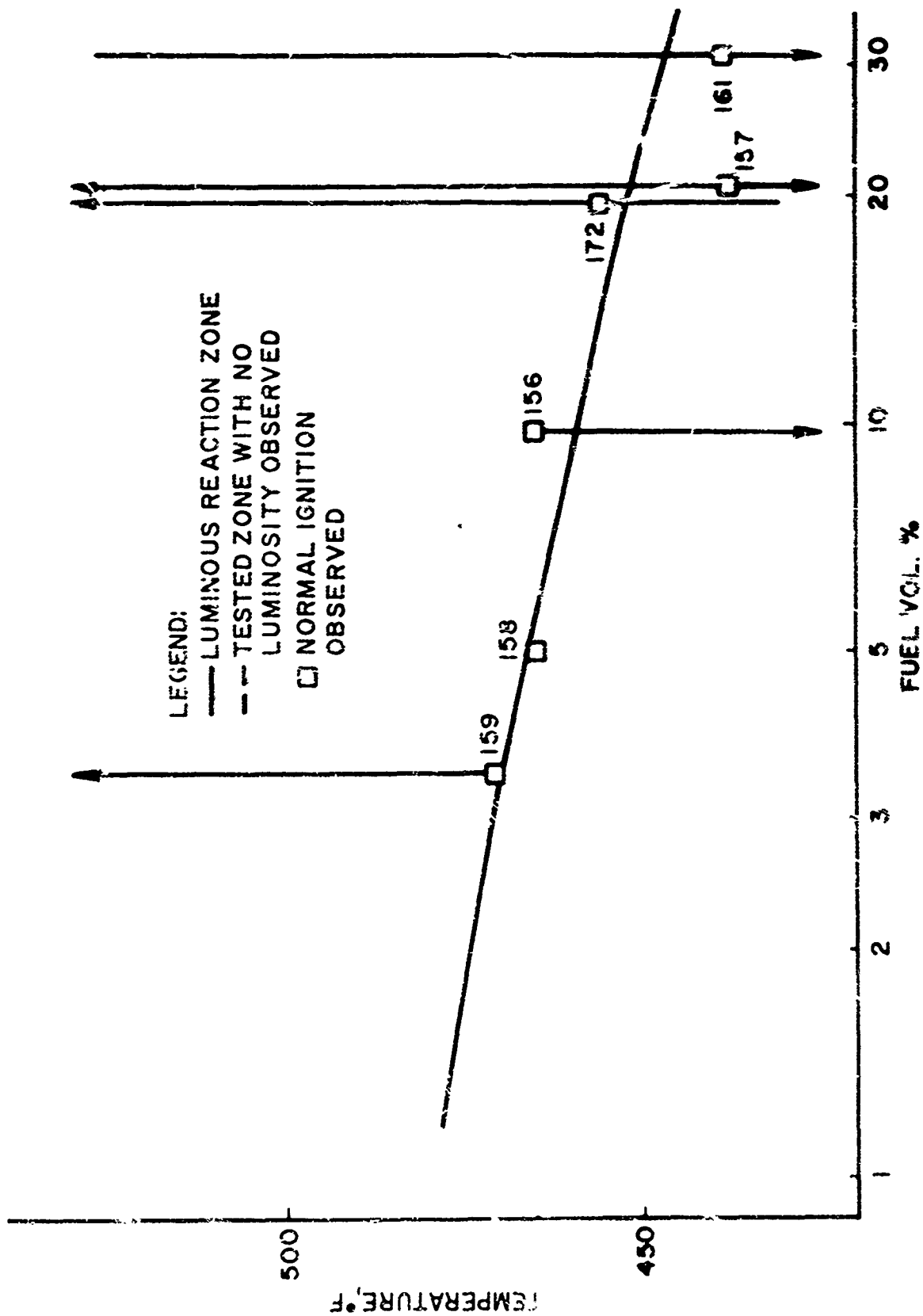
Figure 30. Effect of Antistatic Agent on Ignition of JP-5/Air Mixtures at 25,000 feet Altitude. (Table X)

52
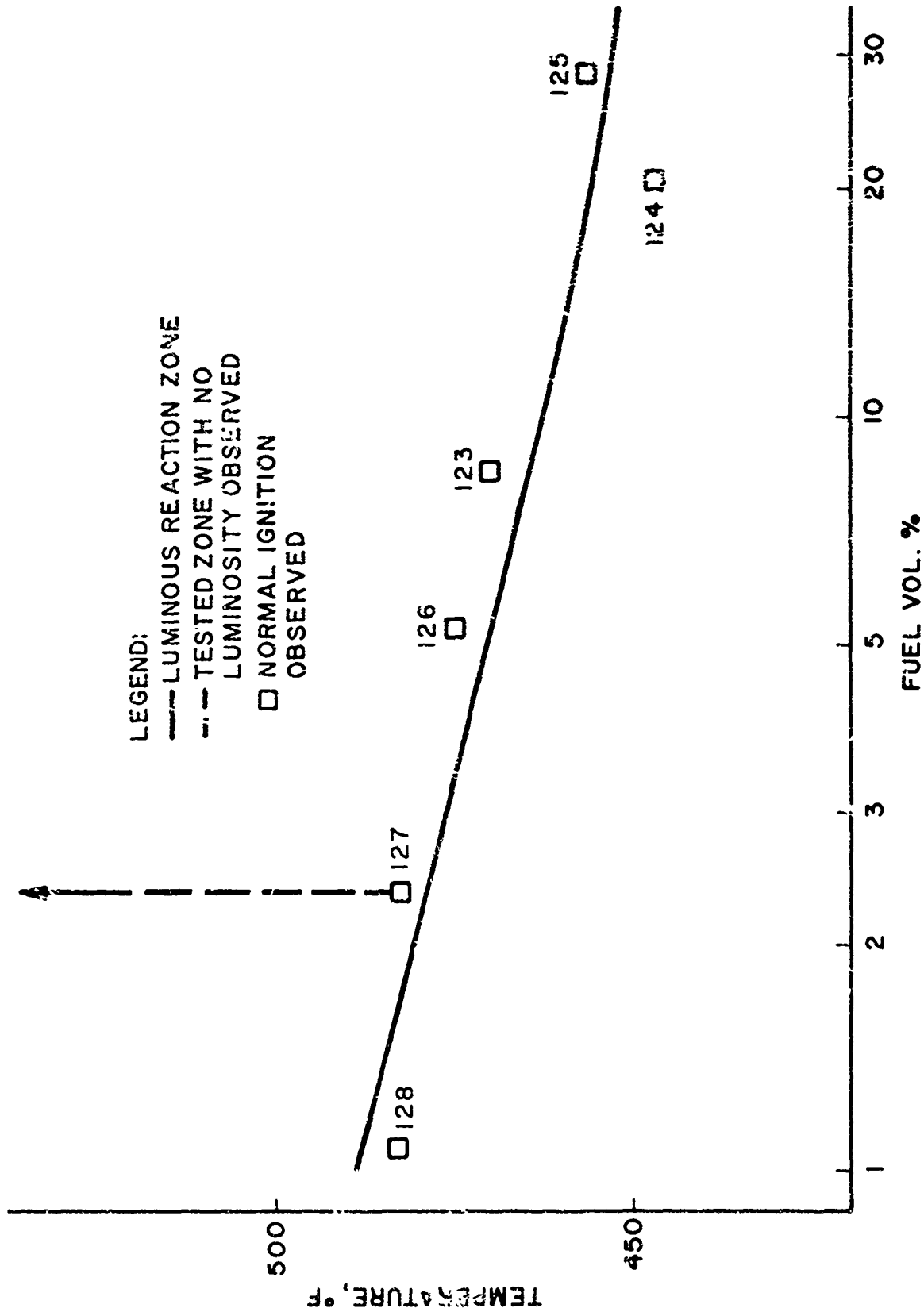
Figure 31. Effect of Anticing Agent on Ignition of JP-5/Air Mixtures at 25,000 feet Altitude. (Table X)
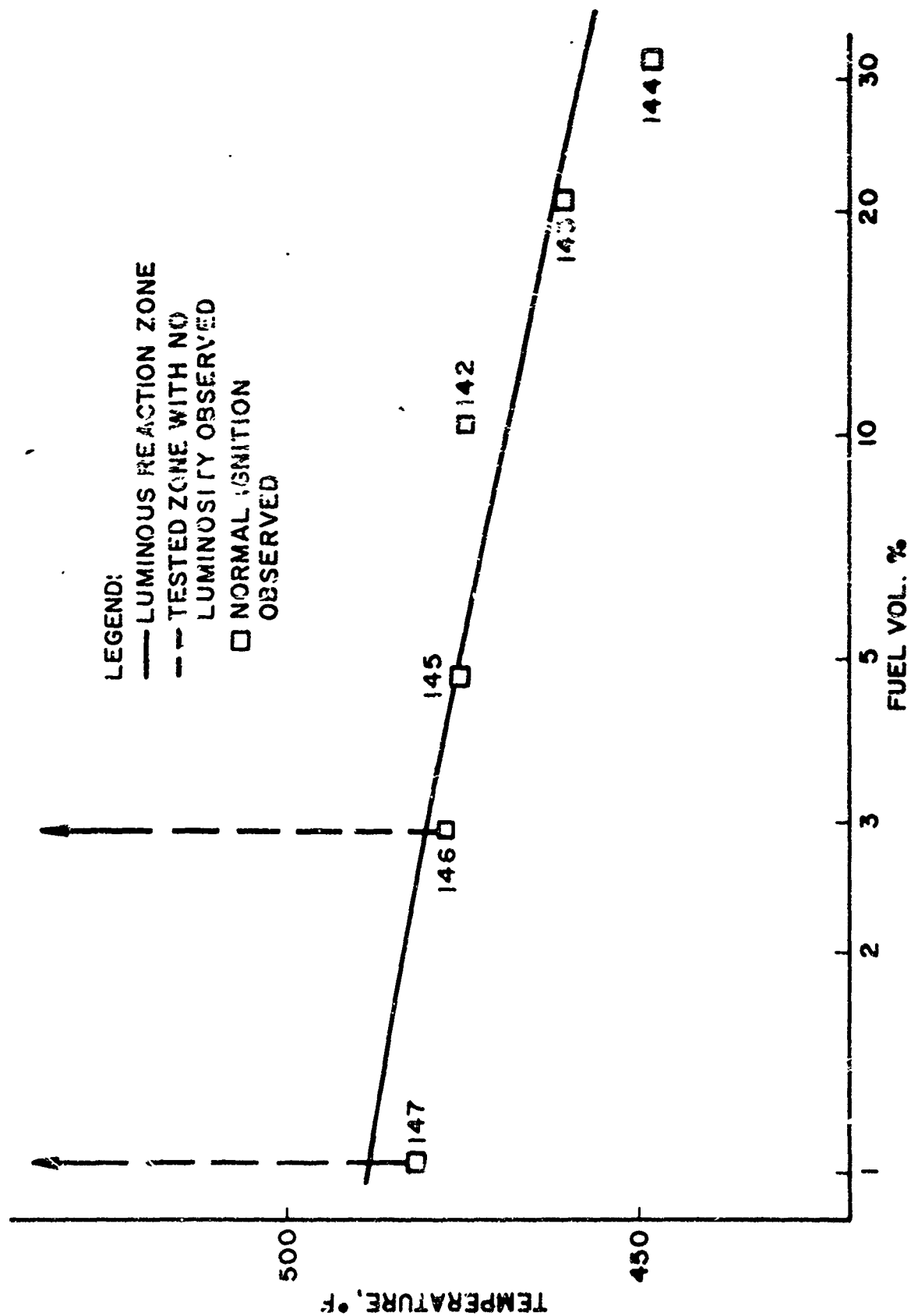
Figure 32. Effect of Lubricity Additive on Ignition of JP-5/Air Mixtures at 25,000 feet Altitude. (Table X)
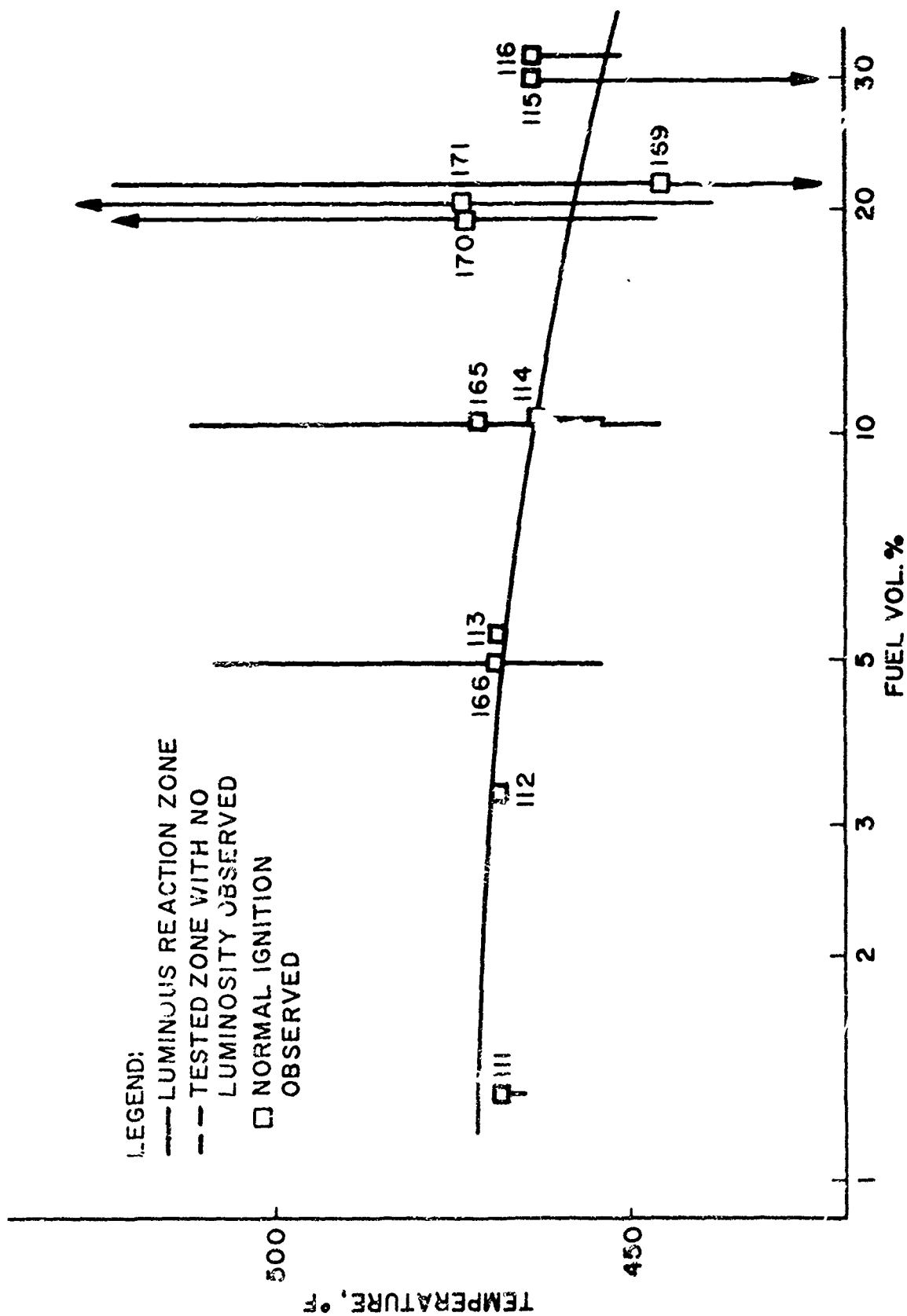
Figure 33. Effect of Corrosion Inhibitor on Ignition of JP-5/Air Mixtures at 25,000 feet Altitude.(Table X)
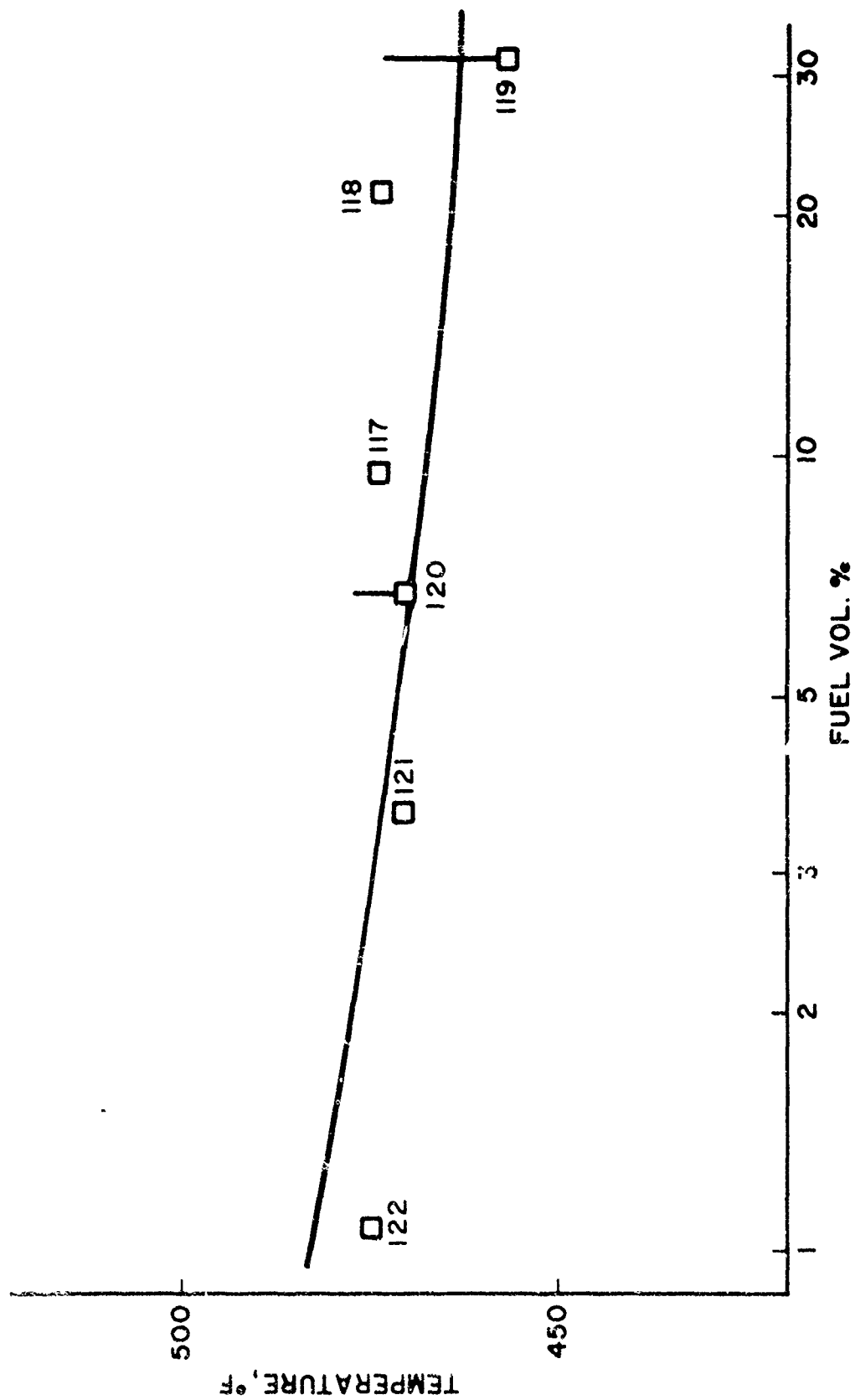
Figure 34. Effect of Antioxidant on Ignition of JP-5/Air Mixtures at 25,000 feet Altitude. (Table X)
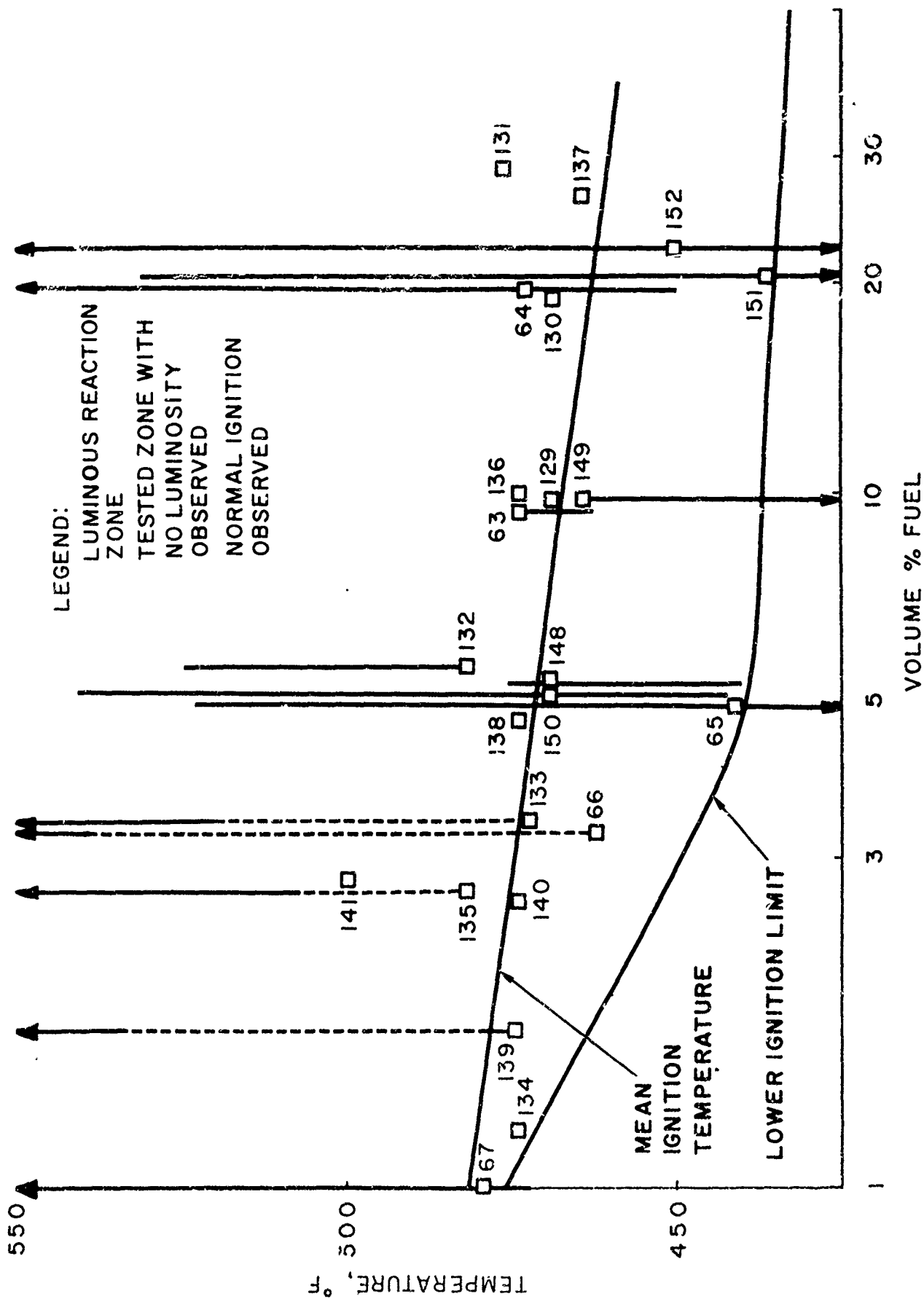
Figure 35.   Ignition Temperatures for JP-5/Air Mixtures
at a Simulated Altitude of 25,000 feet.(Table X)

57
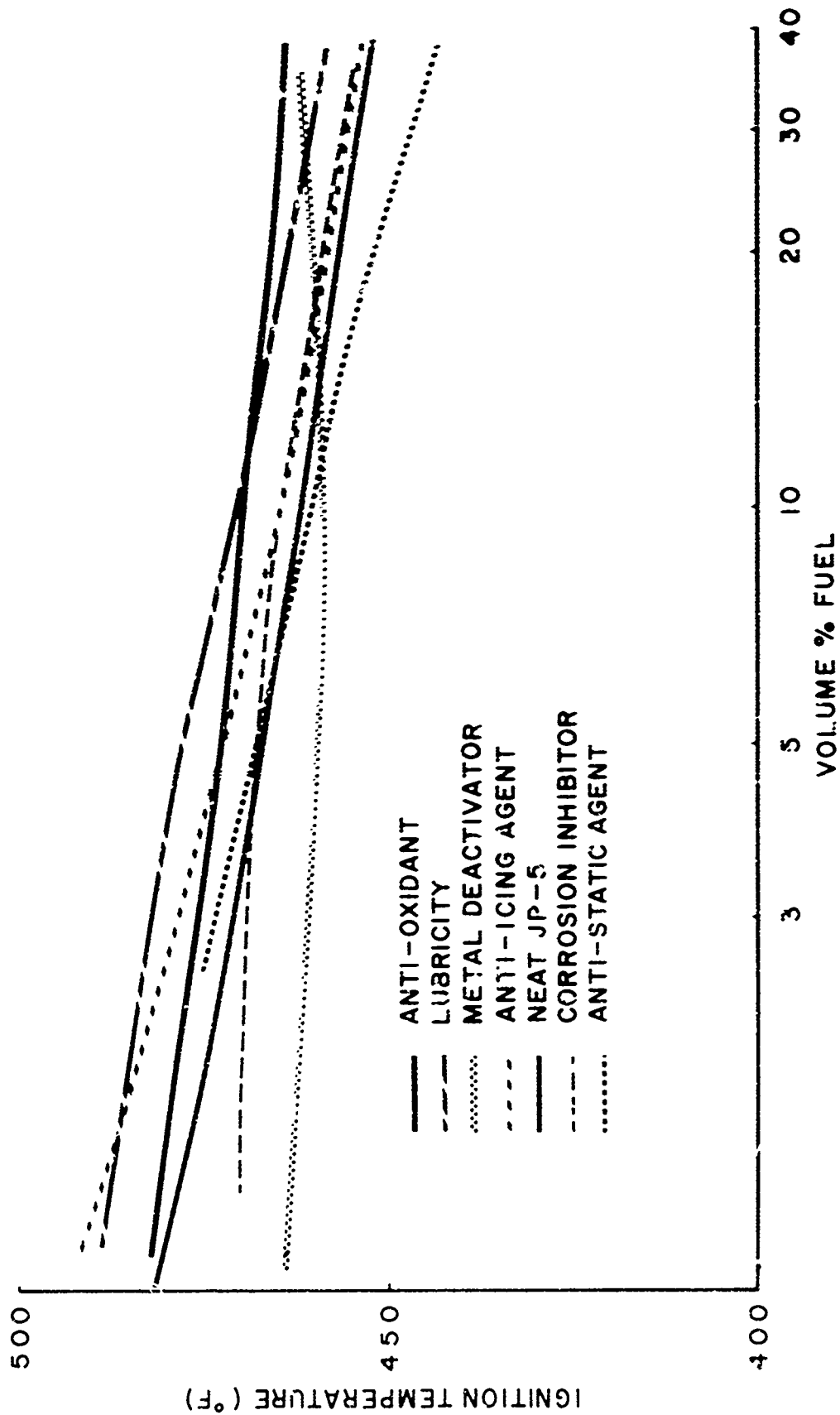
Figure 36.   Comparison of Mean Ignition Temperatures for JP-5 and JP-5
with Various Additives at a Simulated Altitude of 25,000 feet.

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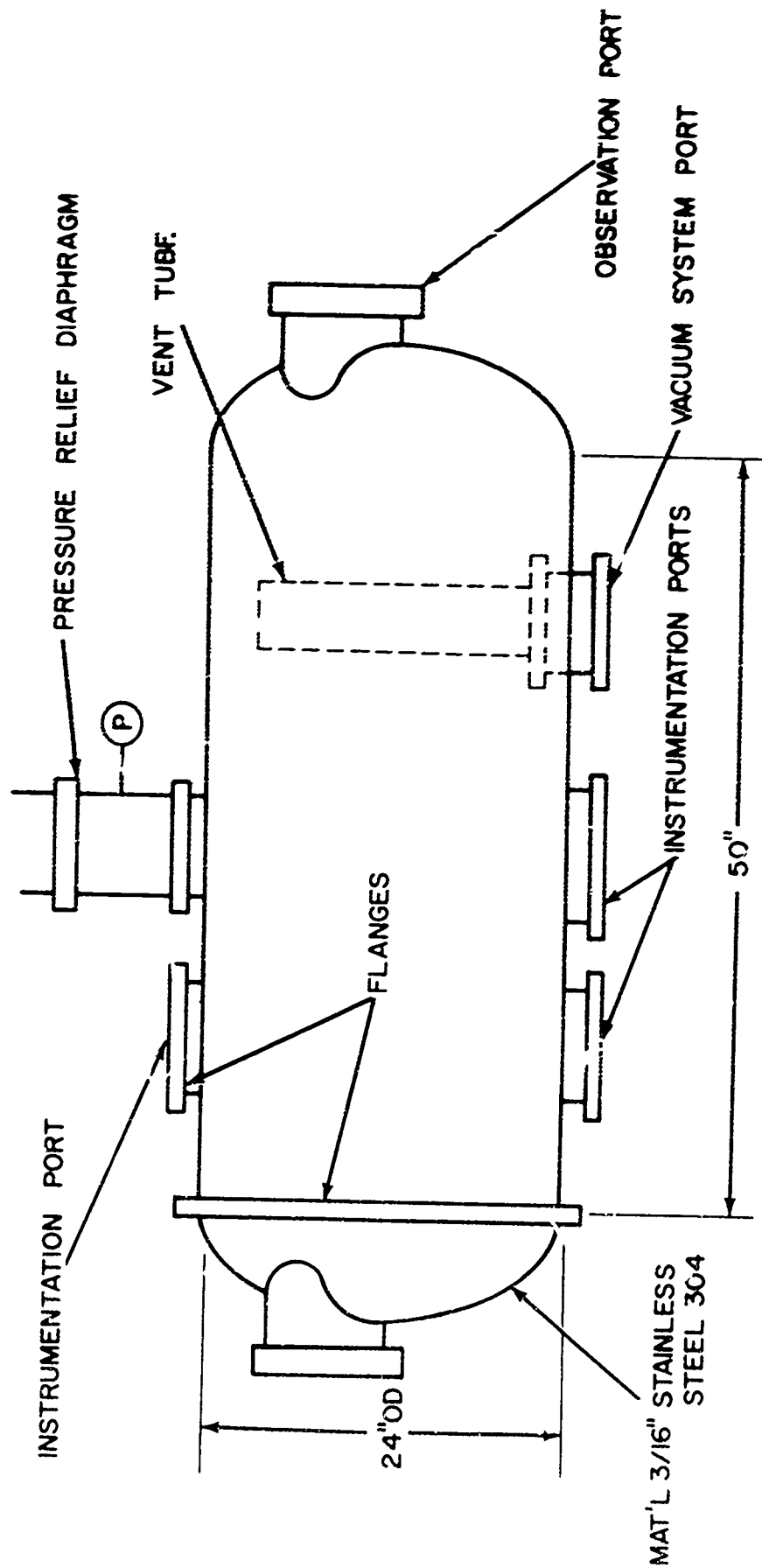
Figure 37. Schematic Representation of Large Test Tank.

PRESSURE RELIEF DIAPHRAGM

VENT TUBE

OBSERVATION PORT

VACUUM SYSTEM PORT

INSTRUMENTATION PORTS

INSTRUMENTATION PORT

FLANGES

INSTRUMENTATION PORT

50"

24"OD

MAT'L 3/16" STAINLESS STEEL 304

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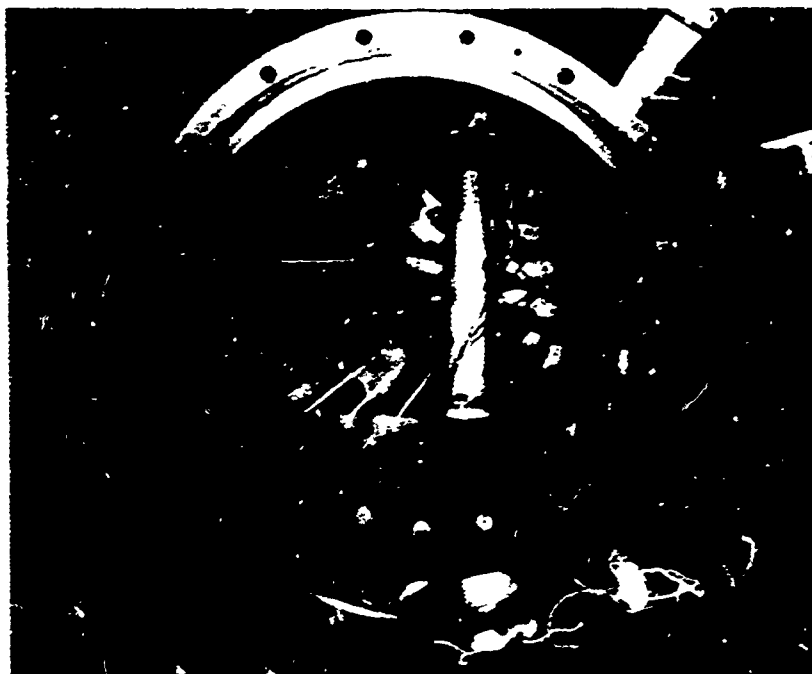
Figure 38. Internal View of Large Test Tank.

Figure 39. External View of Large Test Tank.
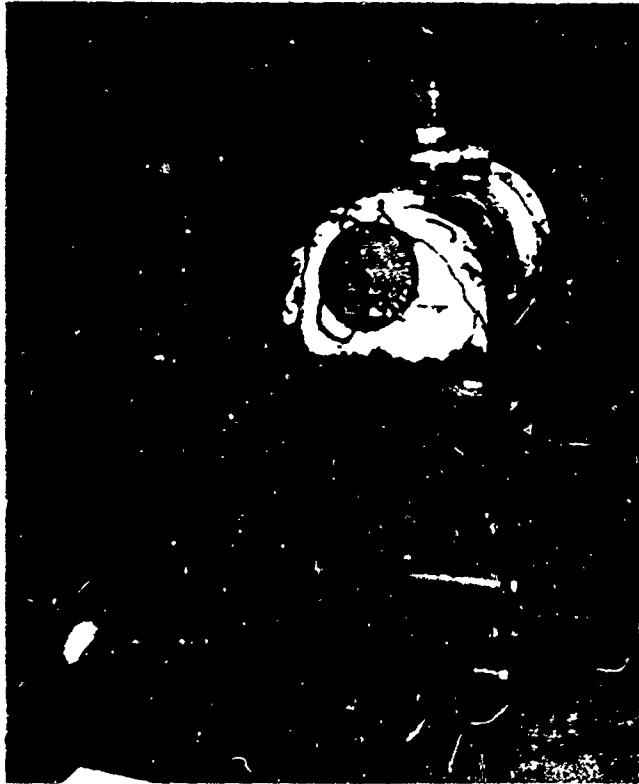
Figure 40.   Test Tank Installed with Insulation in Place.

Figure 41.   View of Test Cell.
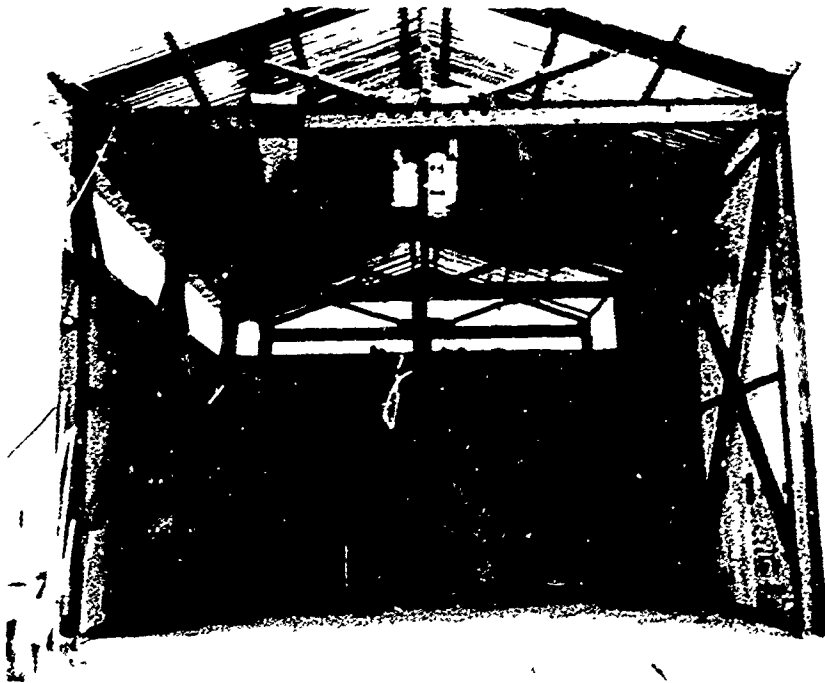
Figure 42.   Equipment Room Adjacent to Test Cell before Completion.

Figure 43.   Completed Test Site.
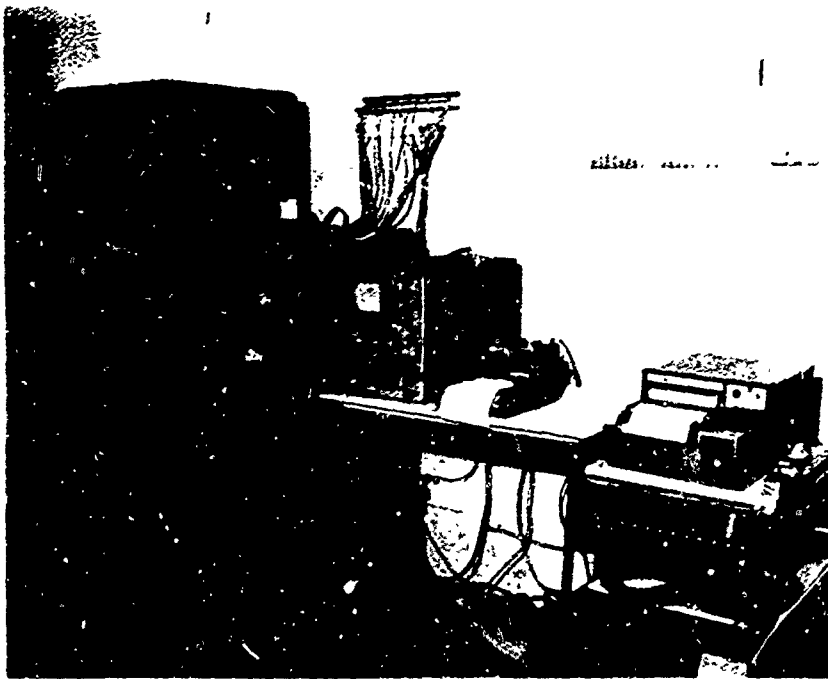
Figure 44.   Instrumentation and Control Equipment Inside Laboratory.
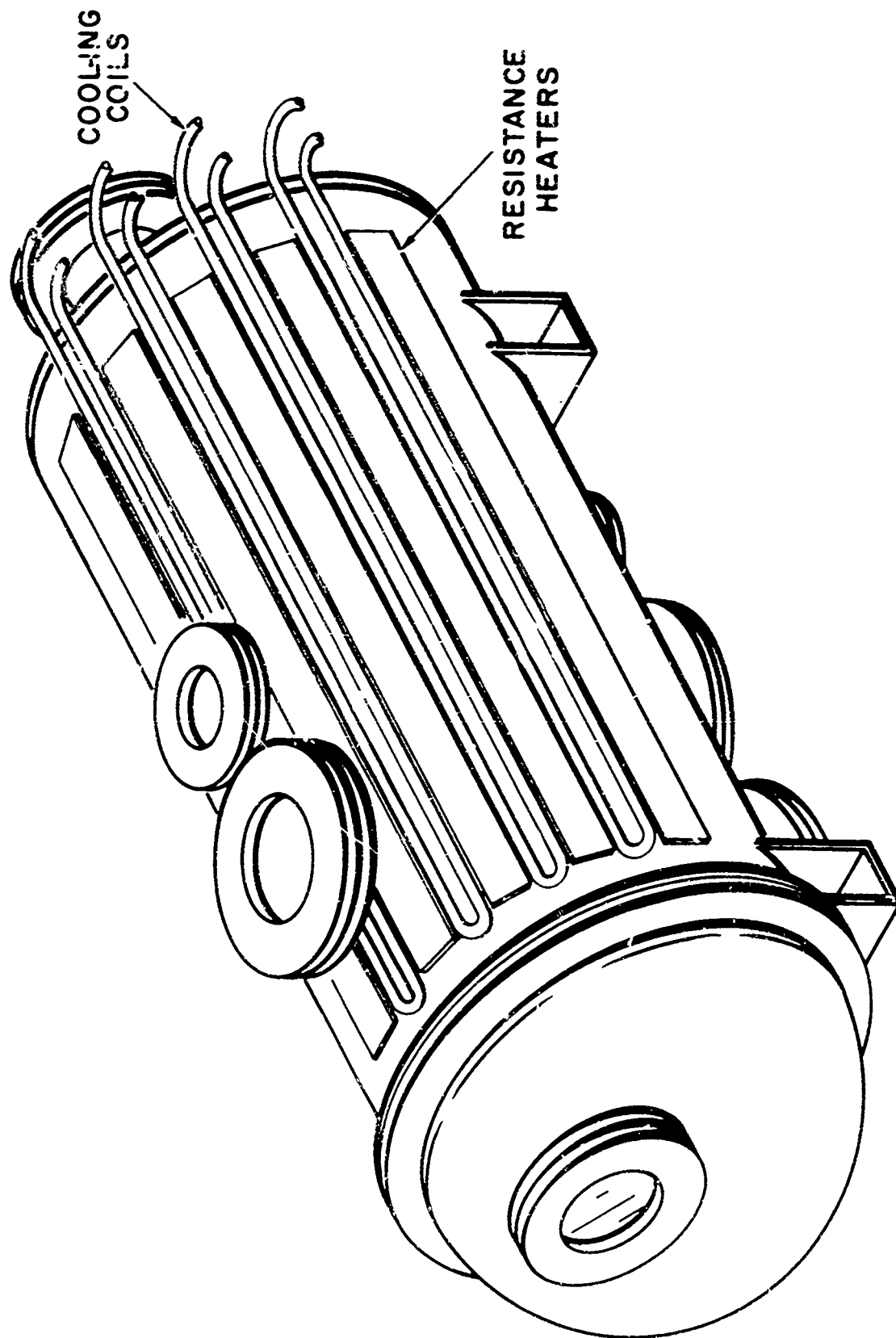
Figure 45.   Arrangement of Heaters and Cooling Coils on Cylindrical
Portion of Unwetted Tank Walls.

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View Port

Cooling Coils

Strip Heaters
Curved to Fit
Surface

2/3 Full

1/2 Full

1/3 Full
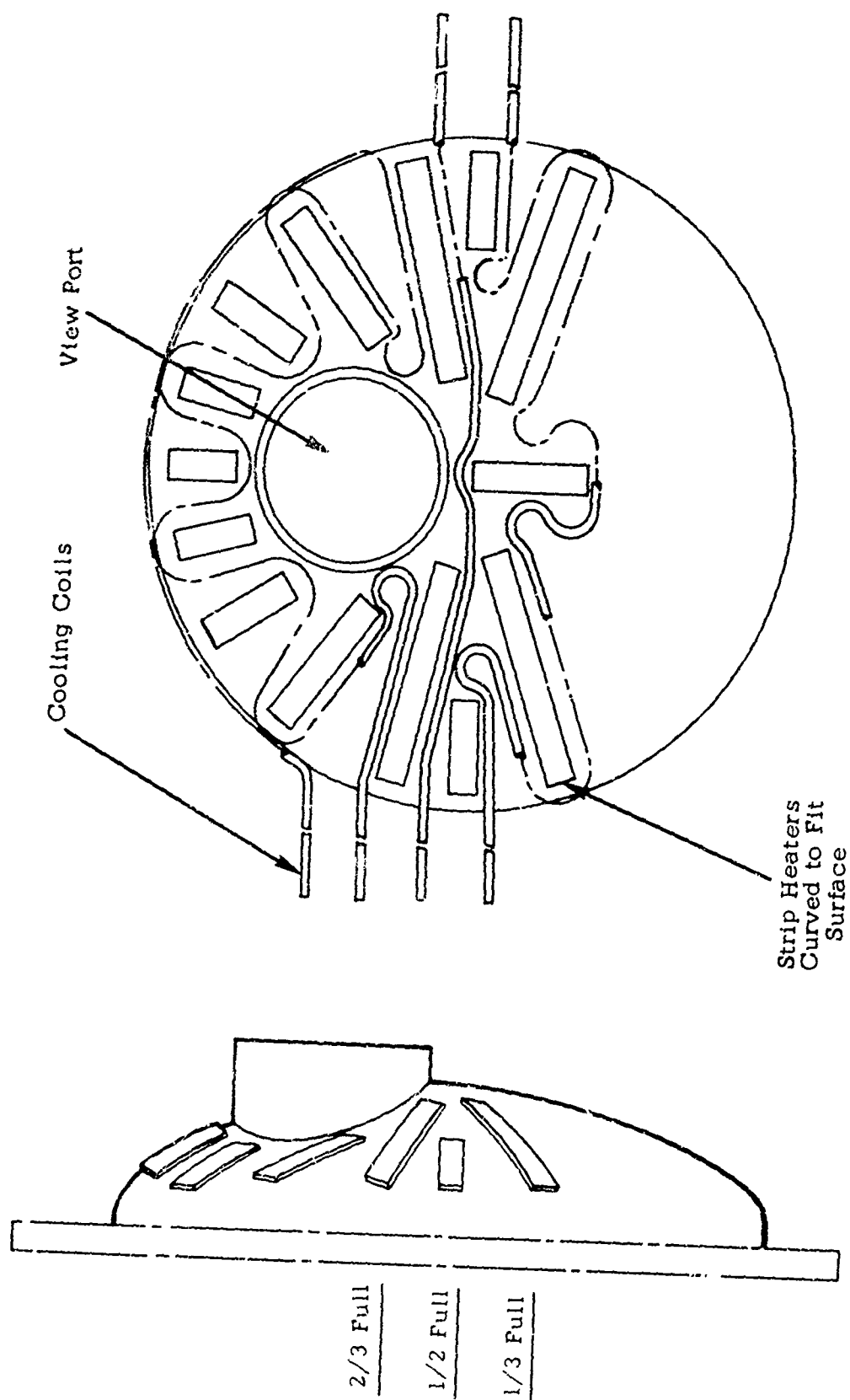
Figure 46. Arrangement of Heating and Cooling Elements on
Ends of Fuel Tank.
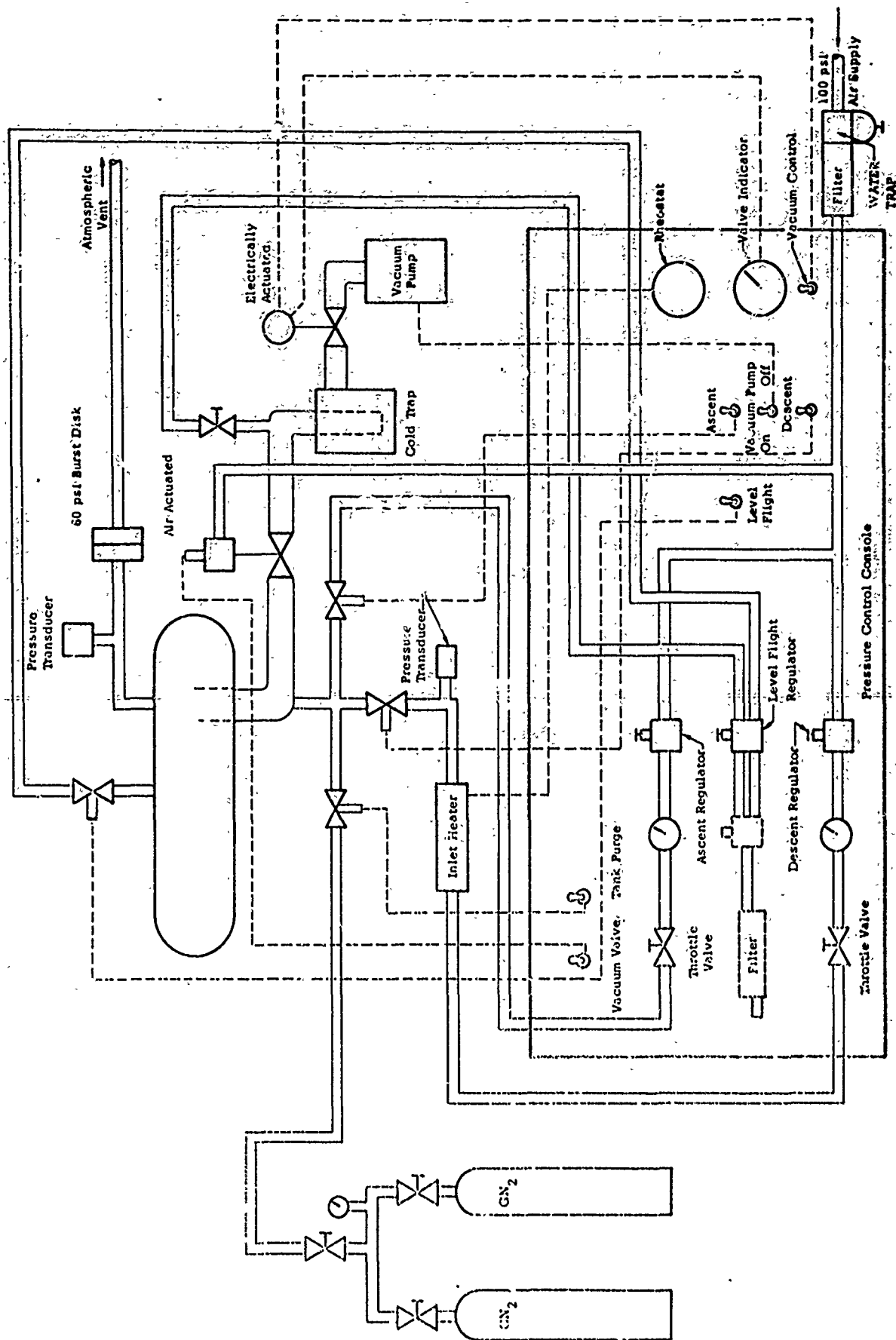
Figure 47. Schematic Diagram of Pressure Control System for Large Tank.

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Figure 48.   Photomultiplier Tube Installed on Test Tank.
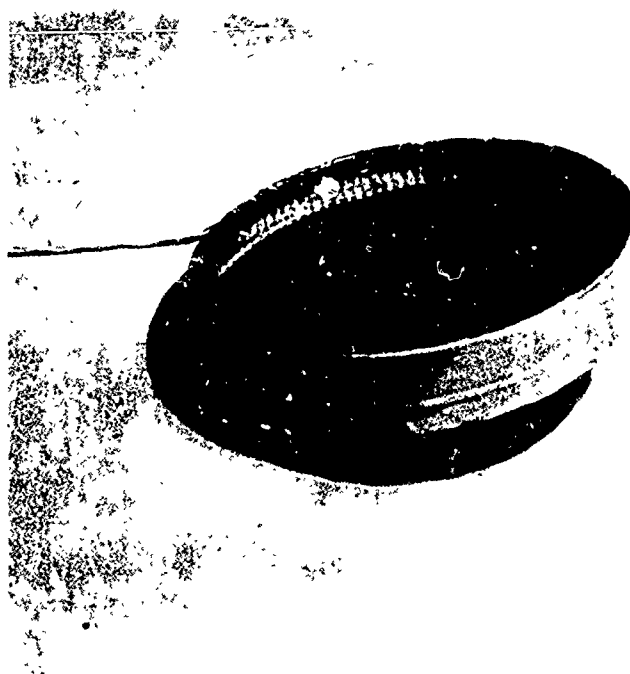
Figure 49.   Observation Port Cover with Test Light.
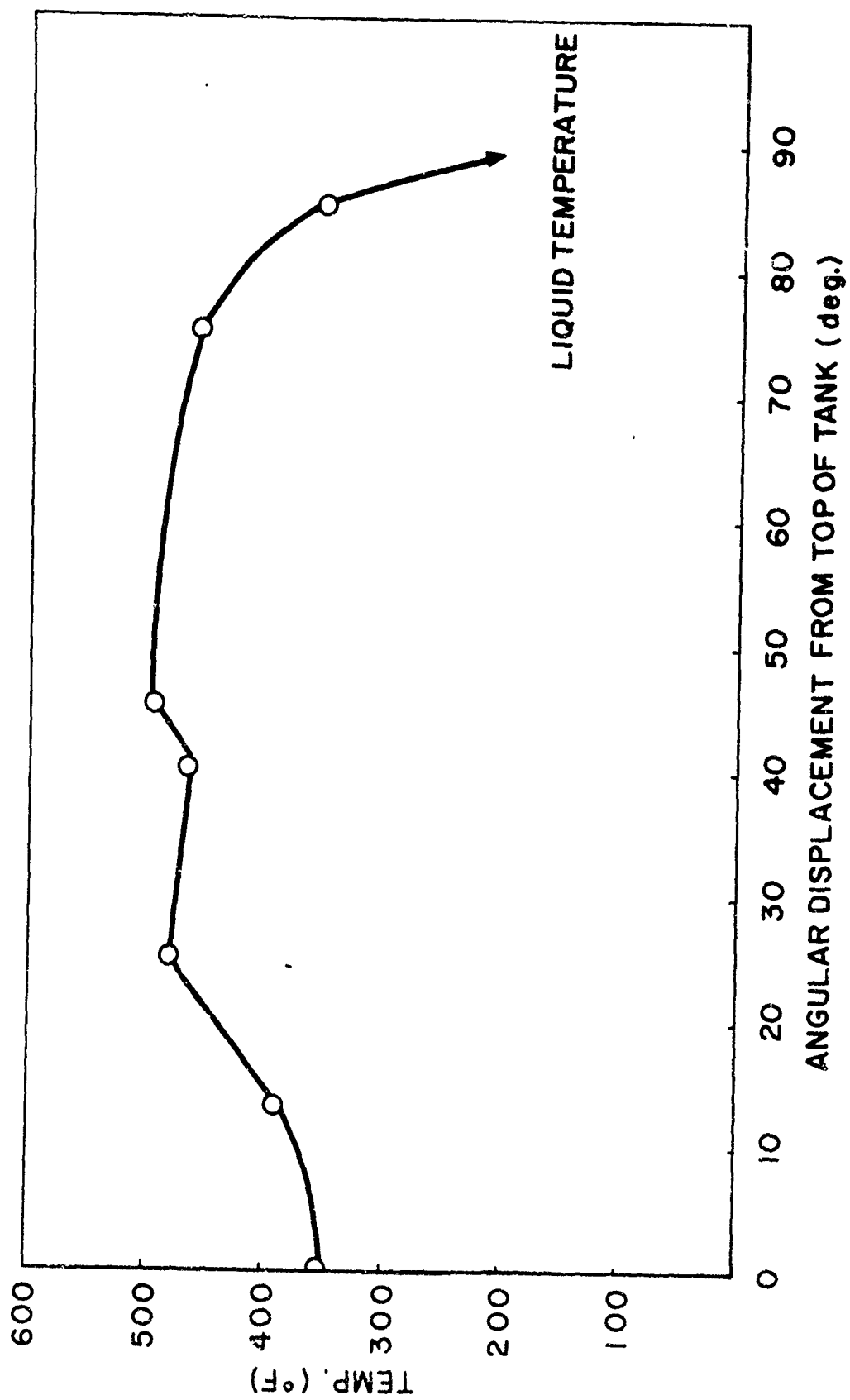
Figure 50.   Circumferential Temperature Distribution of
Unwetted Wall of Test Tank.
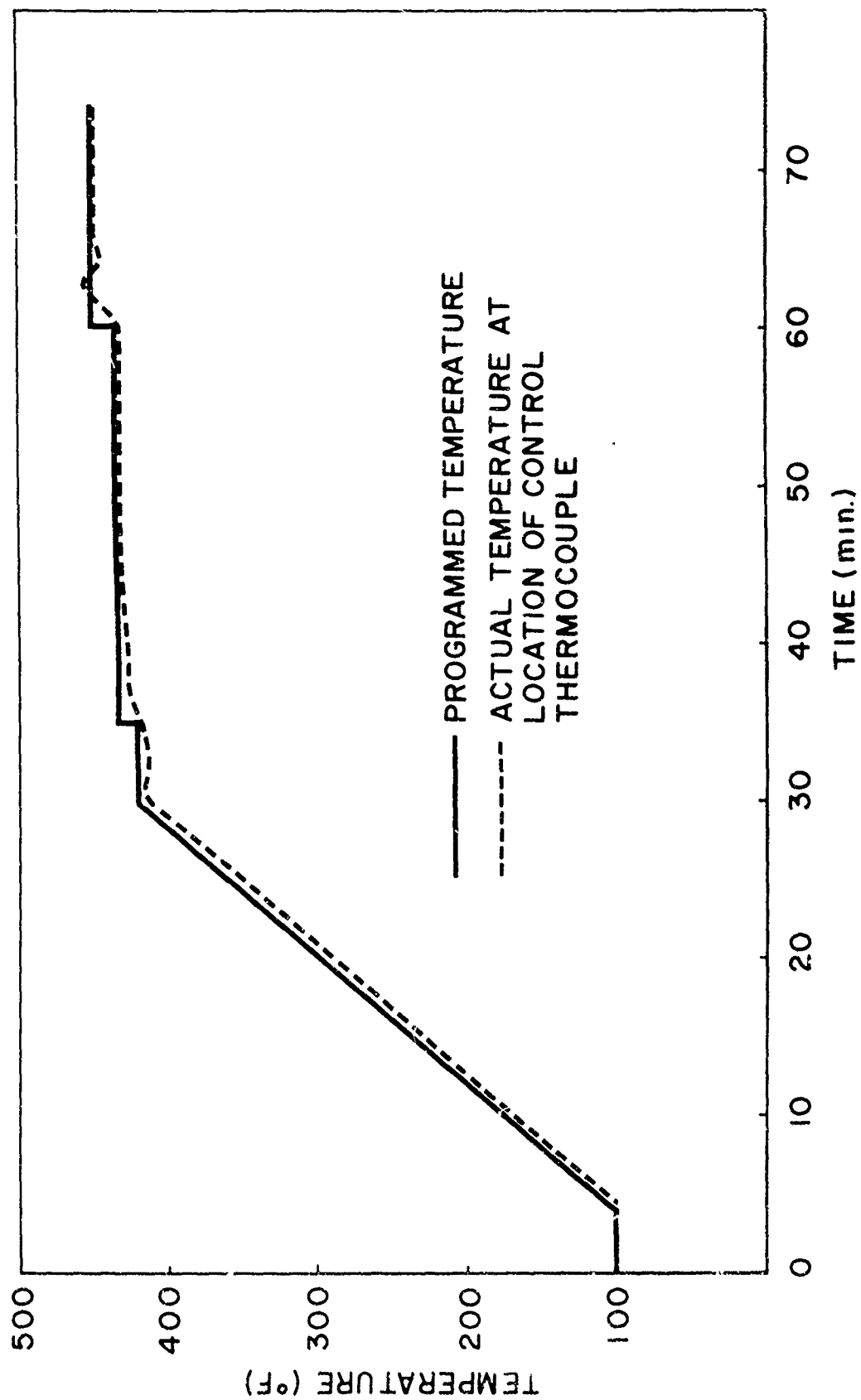
Figure 51. Comparison of Programmed Temperature to Controlled Temperature.
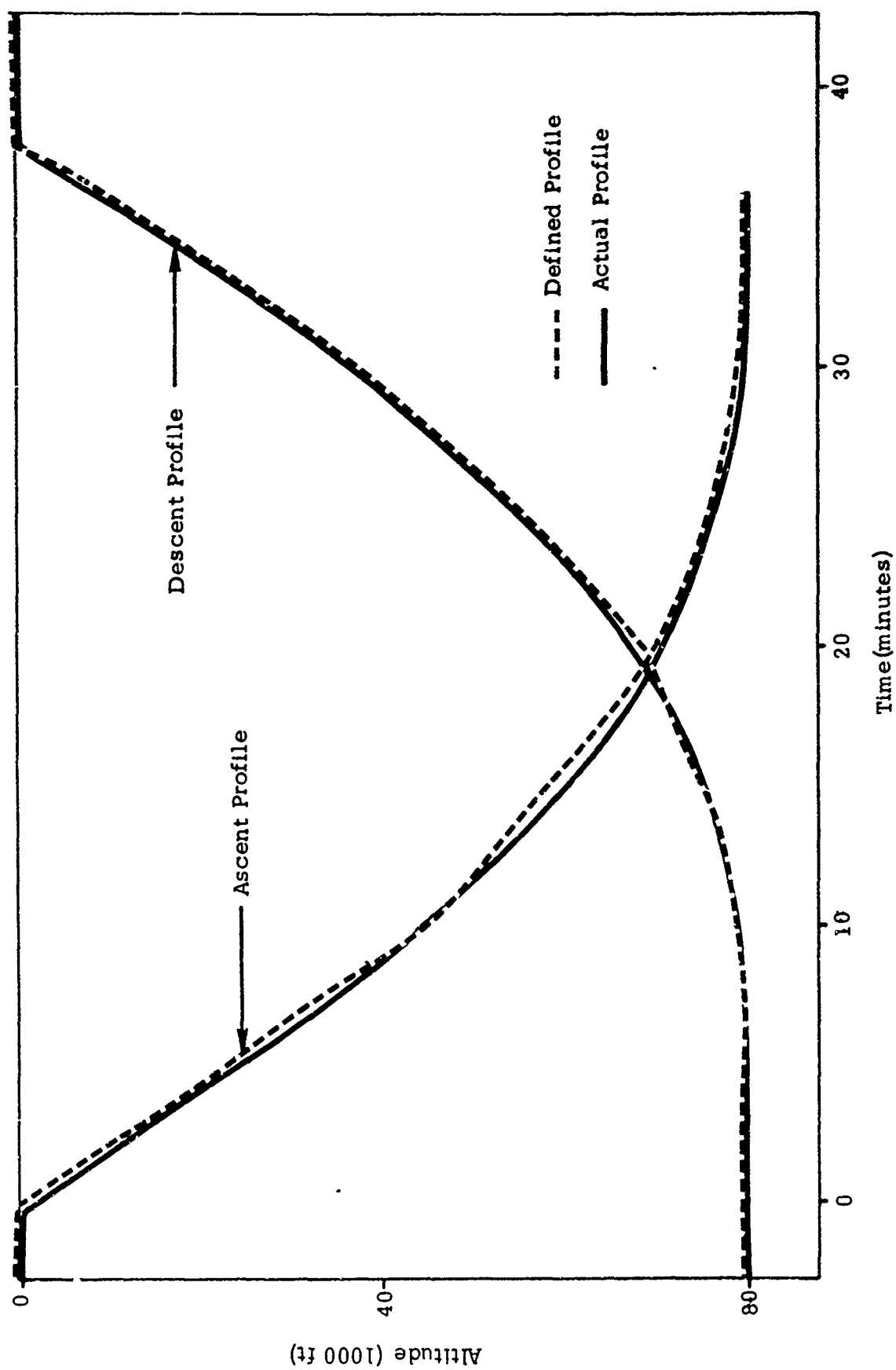
Figure 52.   Controlled Pressure Profiles for Large Test Tank.

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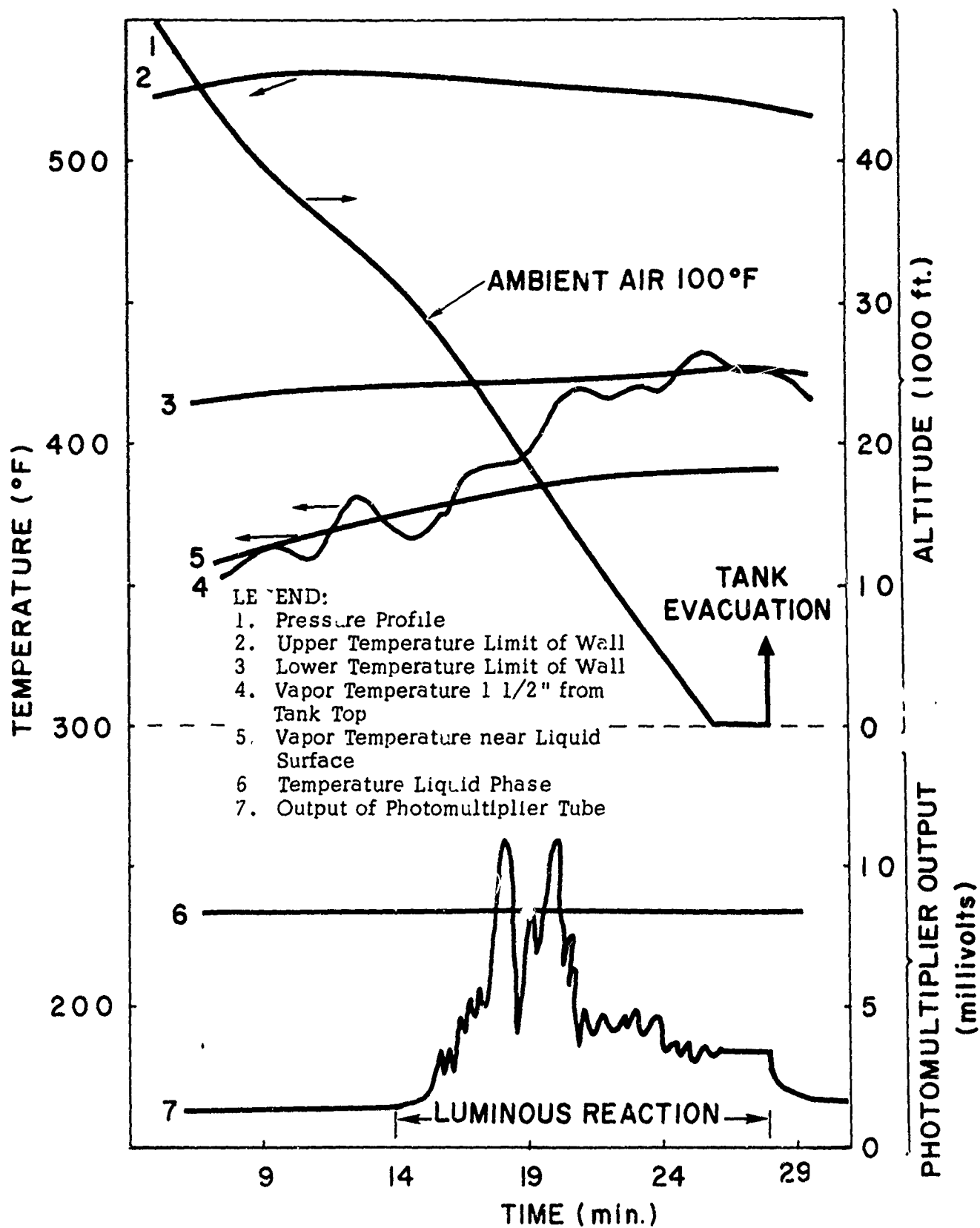
Figure 53.   Representative Data Showing Temperature, Pressure
and Photomultiplier Output During Descent of Test 5C

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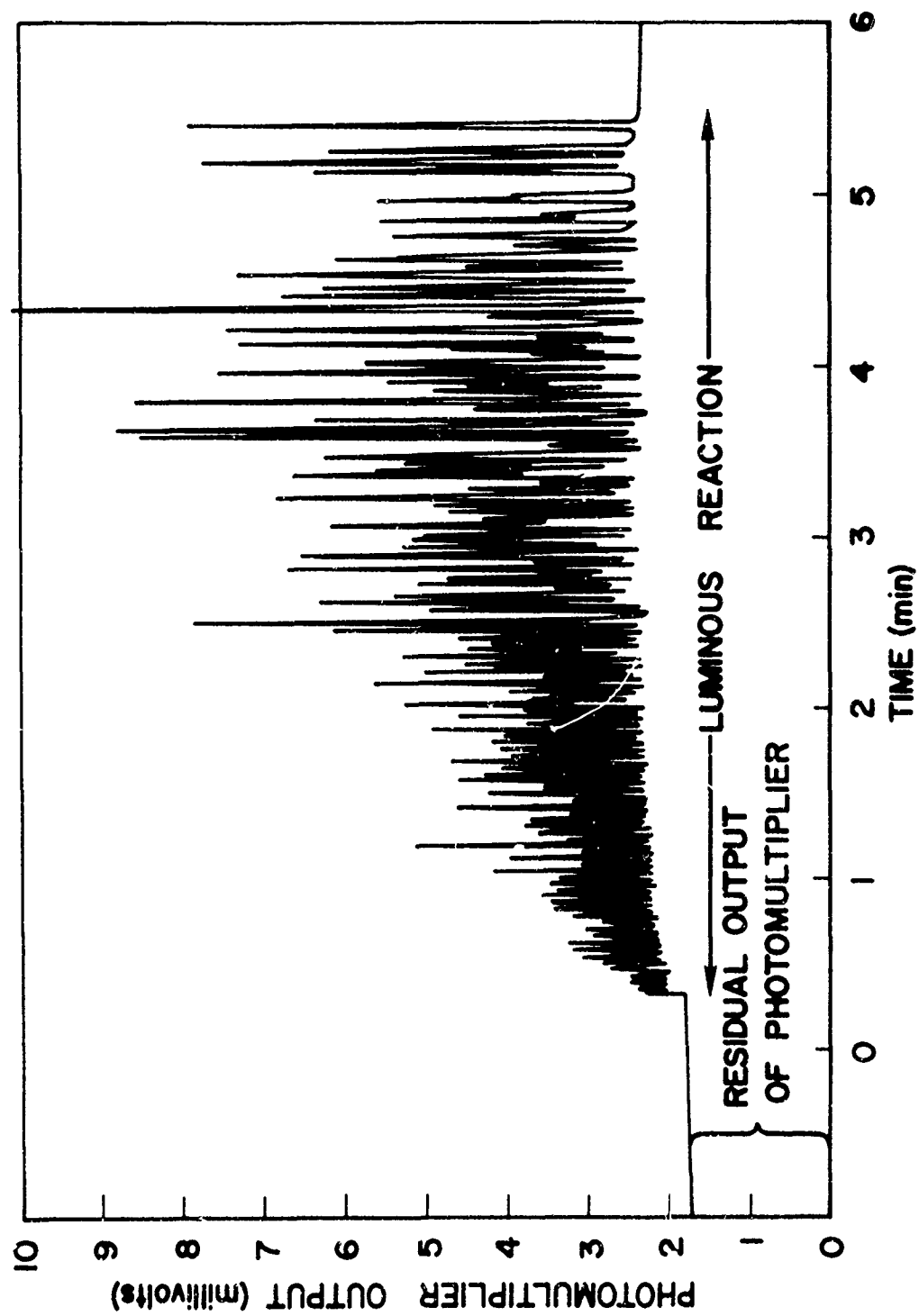
Figure 54.   Photomultiplier Output Indicating Existence of a Luminous Reaction In Test 6A.

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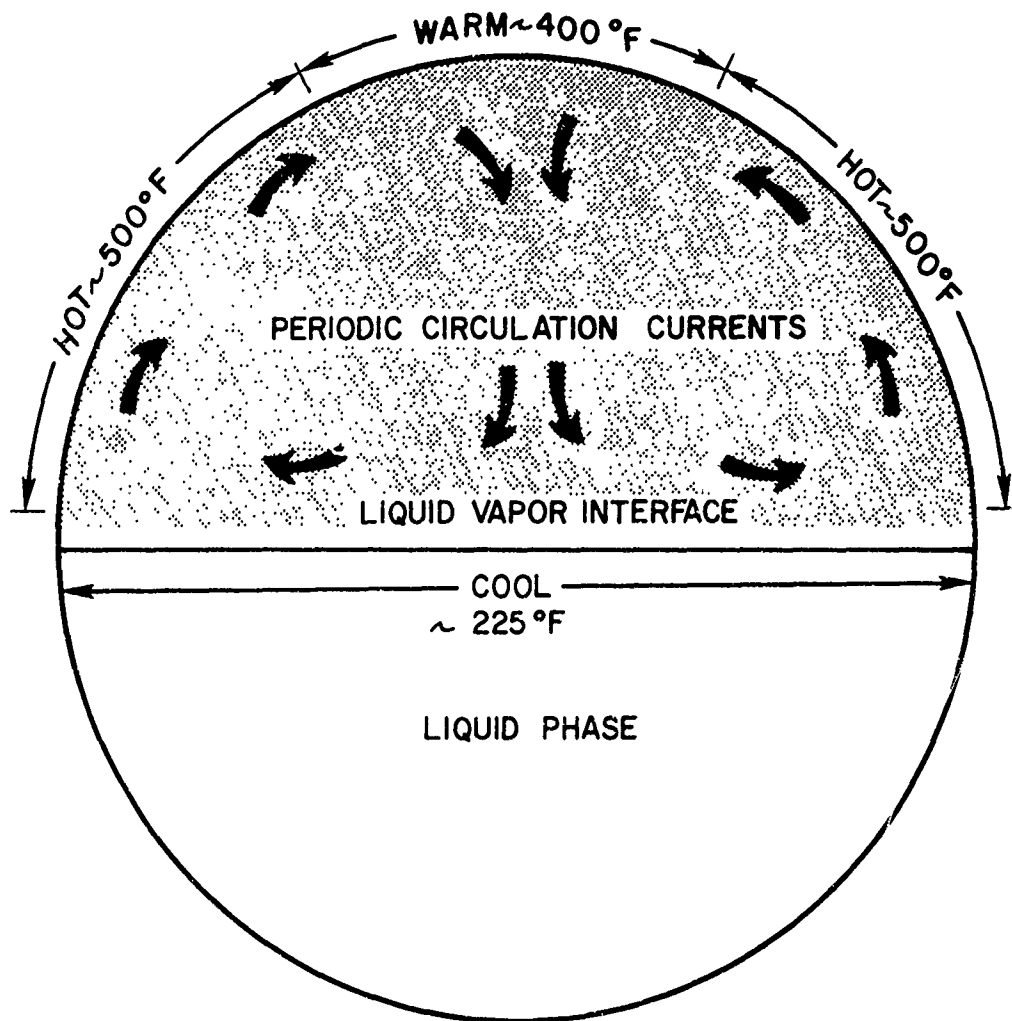
Figure 55.   Schematic Temperature Variation and Flow Pattern
in Vapor Phase of Large Tank.

APPENDIX A

TABLES

Note: Tables VI through X present the Data that was taken using the small tank during the current program. The column headings are explained below:

Vol. % Fuel	Initial fuel composition in fuel/air mixture.
T_{Lum}	Defines range of temperatures in which a luminous reaction was observed.
T_{Flame}	Temperature (^{O}F) at which an ignition was observed.
ΔT_F	Measured temperature change at ignition.
ΔP	Measured pressure change at ignition.
Descent	Designates conditions under which descent profiles were run and also the type of reaction observed. Lum – luminous reaction, and Ign – ignition observed.
W.A.	Tests conducted where output of photomultiplier tube was not suitably amplified.

TABLE I.   ATLANTIC RICHFIELD SPECIFICATIONS
FOR AVIATION TURBINE FUEL, TYPE A

TESTS:

Gravity, °API	40.1
Distillation, °F:	
IBP	355
10% Evap.	381
50%	415
90%	466
95%	480
End Point	516
Residue, %	1.0
Loss, %	1.0
Flash Point, TCC, °F	148
Freezing Point, °F	-62
Viscosity @ -30°F, Cs	10.45
Net Btu/lb.	18,496
Net Btu/gal.	126,994
Corrosion @ 122°F, 3 hrs.	la
Total Acidity, mg KOH/g	0.01
Total Sulfure, wt. %	0.11
Mercaptan Sulfur, wt. %	0.0004
Water Tolerance, ml	Nil, Pass (lb)
Total Potential Residue, mg/100 ml, 16 hrs.	0.8
THERMAL STABILITY:	
Pressure Change, in. Hg(1)	0.05
Preheater Tube Deposits, less than	0
Aromatics, vol. %	17.5
Smoke Point, mm	20.0
Luminometer Number	47

(1) 300°F preheater temperature, 400°F filter temperature,
6#/hr. fuel rate for 5 hrs. duration.

TABLE II. VARIATION OF SINGLE STAGE IGNITION LIMITS WITH TEMPERATURE

Temperature (°F)	Limit Concentration % Volume	
	Lean	Rich
63	1.53	4.50
570	1.22	5.35

It is seen that the composition limits for ignition change only slightly with temperature

TABLE III. FUEL ADDITIVES

Type	Specific Additive	Concentration (Wt.--Basis)	Source
Metal Deactivator	N,N'-disalicylidene-1,2-propanediamine	5.3 ppm	DuPont-Petrochemicals Div.
Antistatic Agent	Shell ASA-3	0.8 mg/l	Shell Oil Co.
Anti-Icing Agent	Ethylene Glycol Monomethyl Ether 99.6 wt %, Glycerol 0.4 wt %	0.1%	Dow Chemical Company
Lubricity Additive	Provided in JP-5 solution by Air Force--identity and concentration not known.		
Corrosion Inhibitor	SANTOLENE "C"	15 ppm	Monsanto Chemical Co.
Antioxidant	2,6-ditertiary-butyl-4-methylphenol	22.35 ppm	DuPont-Petrochemicals Div.

TABLE IV
FUEL SUMMARY FOR LARGE TANK TESTS

Fuel	Source and Specifications	Flashpoint (PMCC) ($^\circ$F)
TFA (Lot 1)	Richfield Oil Company(ASTM-D-1655)	138
JP-5	WPAFB	152
TFA (Lot 2)	Richfield Oil Company (ASTM-D-1655)	122

TABLE V – SUMMARY OF EXPERIMENTAL TESTS USING LARGE SCALE SST TANK SIMULATOR

Test No.	Fuel	Type of Flight Profile[a]	Flame Observed	Flame Duration (min)	Descent Rate Ft/min	T Wall[c] °F (see Fig. 1)		Altitude (1000 ft)	T Liquid °F	Max Gas Phase Temp. °F
1	TFA Lot #1	Complete	Not recorded		2500					
2	"	"	None confirmed		2500	340	390	22	218	320
						320	360	0	218	320
3	"	"	None		5000	400	505	25	205	350
						285	360	0	200	270
4	"	"	None		2500	370	430	22	205	325
						340	390	0	225	340
5A	JP-5	"	None		2500	355	425	25	200	330
						325	385	0	220	300
5F	"	Descent Only	Cool	5	4500	405	520	28	229	370
						410	515	5	229	405
5C	"	"	Cool	13	3000	420	525	32	235	360
						425	515	0	235	420
5D	"	"	Cool	10	3500	425	525	35	242	370
						415	480	0	242	430
6A	TFA Lot #2	"	Cool	5	3600	400	505	22	212	350
						400	500	4	213	380

a. "Complete" refers to the inclusion of ascent, level-flight and descent portion in the profile.

b. This data is for the descent portion of the flight profile.

c. Left hand column is temperature along colder top surface of tank wall. Right hand column represents highest temperature on remainder of unwetted wall (see Figure 1).

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TABLE VI. TEST RESULTS FOR IGNITION BOUNDARIES OF TFA-AIR MIXTURES

Test No.	P_{Total} (mm Hg)	(1000 ft)	Vol. % Fuel	T_{Lum} (°F)	T_{Flame} (°F)	ΔT_F (°F)	ΔP (mm Hg)	$\frac{\Delta P}{P_T}$	Descent Rate ft/min	Descent Flame
1	746	0	1.2	W.A.	527	85	--	--	--	--
5	751	0	1.0	W.A.	500	104	--	--	--	--
28	751	0	1.0	W.A.	482	162	1350	1.80	--	--
10	350	20	1.0	W.A.	482	0	40	.11	--	--
35	282	25	1.0	482–608	500	16	37	.13	1000	none
26	141	40	1.0	--	495	--	--	--	--	--
37	141	40	1.5	464–509	none	--	--	--	4300	none
57	142	40	1.0	495–605	500	--	--	--	--	--
58	141	40	2.0	--	500	--	--	--	3500	none
56	54	60	1.0	527–576	none	--	--	--	4000	none
4	750	0	3.0	W.A.	498	62	--	--	--	--
29	751	0	3.1	none	460	80	1370	1.83	--	--
11	350	20	4.1	W.A.	491	31	775	2.21	--	--
31	282	25	2.7	441–590	441	23	83	.29	--	--
32	282	25	2.9	446–484	446	90	323	1.15	--	--
38	141	40	3.6	none	482	6.5	6.5	.05	6000	none
47	54	60	3.9	509–555	none	--	--	--	19,000	Lum.
54	21	30	3.0	none	none	--	--	--	13,000	Lum.
55	21	80	3.1	none	none	--	--	--	160,000	Lum.
6	750	0	5.0	W.A.	482	54	--	--	--	--
33	282	25	5.0	462–521	482	94	435	1.54	1000	none
16	141	40	5.6	W.A.	496	0	22	1.56	--	--
25	141	40	5.3	W.A.	495	--	--	--	--	--
39	141	40	5.2	none	482	58	2254	1.80	17,000	Lum.
46	54	60	4.8	510–536	none	--	--	--	20,000	Lum.

TABLE VI. Test Results for Ignition Boundaries of TFA-Air Mixtures, (continued)

Test No.	P_Total (mm Hg)	(1000 ft)	Vol.% Fuel	T_{Lum} (°F)	T_{Flame} (°F)	ΔT_F (°F)	ΔP (mm Hg)	$\frac{\Delta P}{P_T}$	Descent Rate ft/min	Flame
30	751	0	10.6	446–490	464	54	615	.82	--	--
12	350	20	10.8	W.A.	489	16	350	1.0	--	--
34	282	25	10.0	none	482	--	--	--	1000	none
17	141	40	9.8	W.A.	496	--	23	.16	--	--
40	141	40	10.1	482–567	491	--	--	--	4500	Ign.
43	54	60	9.2	508–524	none	--	--	--	16,000	Lum.
53	21	80	14.1	none	none	--	--	--	12,500	Lum.
13	350	20	17.5	W.A.	495	22	137	.39	--	--
15	350	20	18.0	W.A.	482	18	455	1.30	--	--
36	282	25	24.4	423–540	473	41	45	.16	1000	none
20	141	40	20.0	W.A.	496	0	42	.30	--	none
21	141	40	20.5	W.A.	486	0	26	.18	5000	none
24	141	40	22.0	W.A.	496	0	24	.17	5000	none
41	141	40	20.0	468–554	484	--	--	--	10,000	Lum.
51	141	40	24.9	490–585	500	--	--	--	7800	Lum.
44	54	60	20.9	500–530	520	--	--	--	15,600	Lum.
50	21	80	20.8	none	none	--	--	--	13,000	Lum.
52	21	80	22.9	none	none	--	--	--	--	--
18	141	40	33.2	W.A.	496	0	25	.17	--	--
19	141	40	29.0	W.A.	464	0	24	.17	--	--
22	141	40	30.0	W.A.	486	0	25	.17	5000	none
42	141	40	30.4	483–520	495	--	--	--	10,000	Lum.
45	54	60	29.5	505–538	none	--	--	--	15,000	Ign.
48	221	80	32.5	none	none	--	--	--	33,000	Ign.
23	141	40	41.8	W.A.	478	0	4.5	.03	5000	none
27	54	60	40.0	W.A.	536	--	--	--	--	--
49	21	80	40.0	none	none	--	--	--	33,000	Ign.

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TABLE VII. TEST RESULTS OF IGNITION BOUNDARY STUDIES FOR JP-5 FUEL-AIR MIXTURES

Test No.	Vol. % Fuel	P_{Total} (mm Hg)	P_{Total} (1000 ft)	T_{Lum} (°F)	T_{Flame} (°F)	ΔT_F (°F)	ΔP (mm Hg)	$\frac{\Delta P}{P_T}$	Descent Rate (ft/min)	Flame
75	1.0	750	0	457-536	464	--	--	--	--	--
67	1.0	280	25	473-631	480	--	--	--	17,500	none
134	1.2	282	25	none	474	35	615	2.18	--	--
139	1.7	282	25	537-572	475	33	100	.35	--	--
73	1.0	141	40	482-504	489	--	--	--	--	--
82	1.0	54	60	none	none	--	--	--	--	--
87	1.0	21	80	none	none	--	--	--	9,000	none
76	3.0	750	0	439-543	446	--	--	--	--	--
66	3.3	280	25	492-593	462	--	--	--	5,000	none
133	3.3	282	25	521-559	472	46	89	.32	--	--
135	2.7	282	25	509-566	482	16	28	.10	--	--
140	2.6	282	25	none	474	94	421	1.50	--	--
141	2.7	282	25	none	500	72	423	1.50	--	--
72	3.0	141	40	482-563	487	--	--	--	14,000	Lum.
80	3.0	54	60	507-547	518	--	--	--	4,300	none
86	3.0	21	80	none	none	--	--	--	5,000	none
65	5.0	280	25	428-523	441	--	--	--	3,000	none
132	5.7	282	25	482-525	482	92	442	1.56	--	--
138	4.9	282	25	none	474	89	435	1.54	--	--
148	5.3	282	25	440-475	470	99	454	1.67	--	--
150	5.0	282	25	437-542	470	93	438	1.55	--	--
71	5.0	141	40	482-626	--	--	--	--	--	--
81	5.0	54	60	518-526	525	--	--	--	33,000	Lum.
85	5.0	21	80	none	none	--	--	--	6,600	none

TABLE VII. TEST RESULTS OF IGNITION BOUNDARY STUDIES FOR JP-5 FUEL-AIR MIXTURES
(Continued)

Test No.	Vol.% Fuel	P_{Total} (mm Hg)	(1000 ft)	T_{Lum} (°F)	T_{Flame} (°F)	ΔT_F (°F)	ΔP (mm Hg)	$\frac{\Delta P}{P_T}$	Descent Rate (ft/min)	Flame
74	10.0	750	0	410-500	446	--	--	--	--	--
63	9.8	280	25	459-475	475	--	--	--	1,700	Lum
129	9.7	282	25	none	469	66	372	1.32	--	--
136	9.9	282	25	none	474	61	372	1.32	--	--
149	10.0	282	25	427-464	464	45	282	1.0	--	--
68	10.0	141	40	464-599	472	--	--	--	9,300	Ign.
78	10.3	54	60	470-529	474	--	--	--	6,000	Lum.
84	10.0	21	80	none	none	--	--	--	9,000	none
64	20.0	280	25	450-581	473	--	--	--	3,000	Lum.
130	19.7	282	25	none	469	76	142	.51	--	--
151	20.4	282	25	411-542	437	48	52	.18	--	--
152	22.0	282	25	421-552	450	19	55	.20	--	--
69	20.0	141	40	468-590	482	--	--	--	9,800	Ign.
79	20.0	54	60	489-518	510	--	--	--	16,000	Ign.
83	20.0	21	80	none	none	--	--	--	14,000	Ign.
131	30.0	280	25	none	476	16	36	.13	--	--
137	27.4	282	25	none	464	15	20	.07	--	--
70	30.0	141	40	468-507	471	--	--	--	31,000	Ign.
88	30.0	54	60	500-527	508	--	--	--	14,000	Ign.

TABLE VIII. RESULTS OF TESTS TO DETERMINE THE EFFECT OF WALL-HEATING-RATE, ON THE IGNITION LIMITS OF TFA-FUEL-AIR MIXTURES.

Test No.	Heating Rate (°F/min)	Vol. % Fuel	P_{Total} (mm Hg)	P_{Total} (1000 ft)	T_{Lum} (°F)	T_σ (°F)	ΔT_F (°F)	ΔP (mm Hg)	$\dfrac{\Delta P}{P_T}$
7	1.8	.8	748	0	W.A.	none	--	--	
8	2.5	3.0	748	0	W.A.	none	--	--	
9	1.8	3.7	750	0	W.A.	432	61	1460	1.95
1	20.0	1.2	746	0	W.A.	527	85	--	
5	20.0	1.0	751	0	W.A.	500	104	--	
28	20.0	1.0	751	0	none	482	162	1350	1.80
4	20.0	3.0	751	0	W.A.	498	62	--	
29	20.0	3.1	751	0	none	460	80	1370	1.83
6	20.0	5.0	751	0	W.A.	482	54	--	
62	10.0	3.0	280	25	469-482	482	--	--	
59	9.4	5.0	280	25	480-500	500	--	--	
60	10.1	10.0	280	25	457-497	477	--	--	
61	10.0	20.0	280	25	447-497	477	--	--	
35	20.0	1.0	282	25	482-608	500	16	37	.13
31	20.0	2.7	282	25	441-590	441	23	83	.29
32	20.0	2.9	282	25	446-484	446	90	323	1.15
33	20.0	5.0	282	25	462-521	482	94	94	1.54
34	20.0	10.0	282	25	--	482	58	254	.90
36	20.0	24.4	282	25	423-540	473	41	45	.16

TABLE IX.   RESULTS OF TESTS TO DETERMINE THE EFFECT OF A COOL WALL
ON THE IGNITION LIMITS OF TFA FUEL-AIR MIXTURES

Test No.	$T_{Initial}$	Programmed Wall		Heating Rate ($^\circ$F/min)		Temperatures at Ignition ($^\circ$F)*				
		Upper 1/2 Tank Wall	Lower 1/2 Tank Wall	Upper 1/4 Tank Wall	Lower 3/4 Tank Wall	TC_t^1	TC_t^2	TC_t^3	TC_t^4	TC_v^1
34	300	+20	+20	--	--	505	490	515	510	482
94	300	+20	+20	--	--	500	495	510	505	478
95	300	+20	+20	--	--	480	485	490	485	455
97	350	+20	0	--	--	500	500	355	365	460
96	350	--	--	--	0	510	350	350	350	383
99	250	+20	0	--	--	535	535	250	285	473
98	250	--	--	+20	0	530	245	245	245	309

*See Figure 1 for location of thermocouples

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TABLE X. RESULTS OF TESTS FOR DETERMINING THE EFFECT OF VARIOUS FUEL ADDITIVES ON THE IGNITION BOUNDARY OF JP-5 FUEL-AIR MIXTURES

Test No.	Additive	Vol. % Fuel	P_{Total} (mm Hg)	P_{Total} (1000 ft)	T_{lum} (°F)	T_F (°F)	ΔT_F (°F)	ΔP (mm Hg)	$\frac{\Delta P}{P_T}$
110	Metal Deactivator	1.3	282	25	none	464	26	84	.30
103	"	3.1	282	25	443-459	459	30	110	.39
163	"	4.6	282	25	455-563	478	--	--	--
104	"	6.0	282	25	none	459	90	480	1.70
168	"	6.0	282	25	432-455	455	81	223	.79
107	"	10.0	282	25	none	455	68	305	1.08
162	"	10.4	282	25	455-517	478	--	--	--
167	"	10.2	282	25	432-455	455	72	210	.75
106	"	15.0	282	25	445-458	458	54	145	.51
105	"	16.0	282	25	none	464	54	145	.51
108	"	21.0	282	25	445-458	458	60	127	.45
164	"	20.9	282	25	440-558	473	--	--	--
109	"	30.0	282	25	451-464	464	36	59	.21
111	Corrosion Inhibitor	1.3	282	25	465-468	468	32	72	.26
112	"	3.3	282	25	none	468	86	450	1.60
113	"	5.4	282	25	none	469	90	468	1.66
166	"	4.9	282	25	454-509	470	--	--	--
114	"	10.5	282	25	454-464	464	63	255	.90
165	"	10.3	--	25	446-512	472	--	--	--
169	"	21.5	282	25	415-525	446	54	102	.36
170	"	19.4	282	25	446-565	473	63	107	.38
171	"	19.9	282	25	437-600	473	54	109	.39
115	"	32.0	282	25	417-464	464	18	8	.03
116	"	31.0	282	25	451-464	464	36	51	.18
122	Anti-Oxidant	1.1	282	25	none	474	26	42	.15
121	"	3.6	282	25	none	469	21	85	.30
120	"	6.8	282	25	469	469	99	407	1.44
117	"	9.8	282	25	none	473	17	306	1.09
118	"	21.6	282	25	none	473	19	152	.54
119	"	30.4	282	25	455-474	455	21	27	.10

TABLE X. RESULTS OF TESTS FOR DETERMINING THE EFFECT OF VARIOUS FUEL ADDITIVES ON THE IGNITION BOUNDARY OF JP-5 FUEL-AIR MIXTURES (continued)

Test No.	Additive	Vol.% Fuel	P_{Total} (mm Hg)	(1000 ft)	T_{Lum} (°F)	T_F (°F)	ΔT_F (°F)	ΔP (mm Hg)	$\frac{\Delta P}{P_T}$
128	Anti-Icing Agent	1.1	282	25	none	482	18	81	.29
127	"	2.4	282	25	544-581	482	26	97	.34
126	"	5.3	282	25	none	474	93	442	1.57
123	"	8.5	282	25	none	469	85	310	1.10
124	"	20.1	282	25	none	446	73	67	.23
125	"	29.7	282	25	none	455	36	28	.10
147	Lubricity Additive	1.0	282	25	536-599	481	28	85	.30
146	"	2.8	282	25	538-563	474	51	95	.34
145	"	4.8	282	25	none	475	88	441	1.57
142	"	10.4	282	25	none	475	62	299	1.06
143	"	20.2	282	25	none	459	65	128	.45
144	"	30.2	282	25	none	447	32	14	.05
160	Anti-Static Agent	.7	282	25	510-524	491	13	84	.30
159	"	3.4	282	25	469-604	469	83	407	1.44
158	"	5.0	282	25	none	464	98	432	1.53
156	"	9.7	282	25	393-464	464	81	257	.91
157	"	20.9	282	25	419-545	437	87	95	.34
172	"	20.2	282	25	430-550	460	63	75	.27
161	"	30.5	282	25	401-527	442	59	49	.17

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DOCUMENT CONTROL DATA - R & D		
(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)		

1. ORIGINATING ACTIVITY *(Corporate author)*	2a. REPORT SECURITY CLASSIFICATION
Dynamic Science, a Division of Marshall Industries 1900 Walker Avenue Monrovia, California 91016	Unclassified
	2b. GROUP

3. REPORT TITLE

Supersonic Aircraft Fuel Tank Fire Hazard Investigation

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Final Report - March 31, 1967 to June 30, 1968

5. AUTHOR(S) *(First name, middle initial, last name)*

Norman L. Helgeson and B. P. Breen

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
November 1968	98	8

8a. CONTRACT OR GRANT NO	9a. ORIGINATOR'S REPORT NUMBER(S)
F33615-67-C-1553	
b. PROJECT NO	SN-100-F
c. 3048 Task No. 304807	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d.	AFAPL-TR-68-106

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Air Force Aero Propulsion Laboratory Wright-Patterson Air Force Base, Ohio

13. ABSTRACT The severe operating environment associated with advanced supersonic and hypersonic flight causes conditions which may significantly reduce the fire safety of these flight systems. The new problem areas arise, in part, from the high temperature produced by supersonic flight through the atmosphere and also from new design concepts. The nature and causes of new fire hazard problems were described in detail in Ref. 1 and those areas requiring further study were pointed out in that survey report.

The purpose of this work was to supplement survey reports which could only postulate problem areas but could not define absolute limits. This was accomplished by carrying out experiments which determined the actual conditions for which a potential fire hazard might exist.

The thermal ignition boundaries for two potential SST fuels as a function of fuel/air ratio and pressure were defined using a small (1.5 ft^3) test tank in which the fuel and air were uniformly mixed. The effects of wall heating rates, cool walls, and several typical fuel additives on ignition temperatures were also determined. Finally, a large test tank ($\approx$15 ft^3) was designed and constructed in order that anticipated non-uniformities in internal fuel tank conditions could be simulated by programming dynamic SST flight profiles. It is also anticipated that the large test tank will aid in extrapolating experimental results to full-scale systems. The large tank was tested with several flight profiles and was found to be capable of reliably simulating flight pressures and temperatures profiles. Data runs with the larger tank using two different fuels showed that luminous reactions did appear during the descent portion of simulated SST flight profiles.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Ignition Boundaries						
Additives, Jet Fuel, effect on						
Cool – Flame						
Pressure, effect on						
Supersonic Aircraft						
Hazards, Fuel Tank						
Hazards, Fire and Explosion						
Simulator, Fuel Tank						